Initial_EDA

October 9, 2025

1 Initial EDA for Masters Thesis On Policy Effects on Site-Level Emissions

1.1 Research question / Hypotheses

Core question: > How do discrete environmental policy interventions affect local air-quality outcomes—measured via satellite-derived NO —around major industrial and power-sector emitters across the US and EU?

Sub-questions / hypotheses: - *H1:* Implementation of air-quality regulations (e.g., CSAPR, IED) reduces tropospheric NO in buffers surrounding treated facilities. - *H2:* The magnitude of NO reduction correlates with plant characteristics (fuel type, capacity, presence of controls) and local geography (AlphaEarth embeddings). - *H3:* Seasonal and meteorological conditions (ERA5 winds, boundary layer height) moderate observed changes.

We expect to observe **downward trends** in NO near coal-dominated facilities post-policy and smaller or mixed effects near gas-fired or already-compliant plants.

2 Overview of Datasets

Dataset	Temporal Resolution	Role	Notes / Links
EIA-860 (annual)	Yearly	Static attributes for **US** plants (capacity, primary fuel, optional controls via EnviroAssoc)	Authoritative plant inventory. Used to build the US facility universe and geocodes. EIA-860
EIA-860M (monthly)	Monthly	Operating status / temporal changes	Aligns facility×month activity if we need on/off status. EIA-860M
EPA FRS (optional)	Static	Alternate facility geocodes	Only needed to patch coordinates. FRS
EEA Industrial Emissions Portal – LCP	Annual (wide)	**EU** large-combustion plant attributes & coordinates	EU plant universe. We harmonize to plant-level `capacity_mw` and a coarse `fuel_primary`. EEA LCP

Dataset	Temporal Resolution	Role	Notes / Links
US policy coverage (ARP/CSAPR)	Annual program coverage → **monthly flags**	Policy exposure for **US EGUs**	Pulled from the **EPA EASEY Facilities API**. Canonical codes used: `ARP`, `CSNOX` (annual NOx), `CSNOXOS` (ozone-season NOx), `CSOSG1`, `CSOSG2` (SO G1/G2). We scope to **Electric Utility** or records with an **ORIS** code. Exact effective dates encoded (e.g., `CSNOXOS` starts **May 1** each year).
EU policy coverage (EU ETS)	First compliance year → **monthly flags**	Installation-level exposure for **EU stationary ETS**	Loaded from **EUETS.INFO extracts** via `pyeutl.ziploader`. We keep stationary activities (power/industry) and **exclude aviation/maritime/ESD** using `activity_types.csv`. Effective date = **Jan 1 of first compliance year** for each installation.
TROPOMI NO (S5P)	Daily → Monthly	Outcome variable	Tropospheric NO column density aggregated in Earth Engine.
ERA5 monthly	Monthly	Meteorological controls	Wind, PBLH, temperature, precip.
AlphaEarth (10 m, 64-D annual)	Annual	Geographic embedding controls	Land-use / context embeddings.

Notes on policy timing (we encode exactly): - US: `ARP`, `CSNOX`, `CSOSG1`, `CSOSG2` **Jan 1** of earliest covered year; `CSNOXOS` (ozone season) **May 1** of earliest covered year and **active only May–Sept** each year. - **EU ETS**: annual cap — we use **Jan 1** of the first year an installation appears in compliance (treats all months in/after that year).

EIA-860 is annual, used for structural attributes – whereas *EIA-860M* provides monthly operational data to align with our panel.

2.0.1 Schema Sketch for Policy Panel

```
policy_id         : str   # unique
policy_name       : str
policy_class      : str   # 'cap' | 'standard' | 'lez' | 'other'
sector            : str   # 'power' | 'industry' | 'transport'
region_type       : str   # 'state' | 'country' | 'city'
region_code       : str   # e.g., 'TX', 'DE', city slug
effective_date    : str   # 'YYYY-MM-DD'
season_start_month: int   # 1..12 or blank (NA)
season_end_month  : int   # 1..12 or blank (NA)
source_url        : str
```

From these, we derive flags per facility: `treat_any`, and class-specific `treat_cap`, `treat_standard`, `treat_lez`.

2.1 Rough Causal Diagram

Outcome: **monthly NO near facilities** E_{it}. Causes: **policy exposure** P_{it}, **plant characteristics** X_i, **geographic context** G_{it}, **weather/transport** W_{it}. Lobbying L_{rt} shapes policy and moderates effects. We will estimate staggered-adoption event-studies with facility and month FE.

```
flowchart LR
  subgraph Unobserved Confounders
    direction TB
    Ur(U_rt)
    Ui(U_i)
    Ut(U_t)
  end
  subgraph Exposures / Confounders
    direction TB
    L[Lobbying L_rt]
    X[Plant traits X_i]
    G[Geo context embedding G_it]
    W[Weather / transport W_it]
  end
  subgraph Policies
    direction TB
    P[Policy P_it]
  end
  subgraph Outcome
    direction TB
    E[NO2 outcome E_it]
  end
  Ur -.-> L
  Ui -.-> X
  Ut -.-> P
  Ut -.-> E
  L --> P
```

```
X --> P
G --> P
W --> P
P --> E
X --> E
G --> E
W --> E
L -.-> E
```

2.2 Load facilities and construct plant attributes

2.2.1 USA EIA-860 (2024) files and columns:

- **Plant** — `2___Plant_Y2024.xlsx` Columns we use: **Plant Code**, **Plant Name**, **State**, **Latitude**, **Longitude**.
  (Coordinates live here)
- **Generators (Operable)** — `3_1_Generator_Y2024.xlsx` (sheet **Operable**, header row at index 1)
  Columns we use: **Plant Code**, **Nameplate Capacity (MW)**, **Energy Source 1**.
  (Early simplification: we aggregate generator capacity to plants and infer a plant's primary fuel.)
- **EnviroAssoc (optional abatement flags)** — `6_1_EnviroAssoc_Y2024.xlsx` (sheet **Emissions Control Equipment**, header row at index 1)
  Columns we use: **Plant Code**, **Equipment Type** (coded).
  Codes (from **LayoutY2024 → Reference Tables 7–9, Table 7**):
  - **SR** = Selective Catalytic Reduction → `has_scr=1`
  - **SN** = Selective Non-Catalytic Reduction → `has_sncr=1`
  - **SD** = Spray dryer / dry FGD / semi-dry FGD; **CD** = Circulating dry scrubber → `has_fgd=1`

[47]:
```python
import pandas as pd, numpy as np, os

OUT = "data/out"
os.makedirs(OUT, exist_ok=True)

# --- PLANT (coords, state, id) ---
plant_path = "data/eia8602024/2___Plant_Y2024.xlsx"
plant_us = pd.read_excel(plant_path, sheet_name="Plant", header=1,
                         usecols=["Plant Code","Plant␣
↪Name","State","Latitude","Longitude"])
plant_us = plant_us.rename(columns={"Plant Code":"plant_id","Plant Name":
↪"name","State":"state",
                                    "Latitude":"lat","Longitude":"lon"})
plant_us["country"] = "US"
plant_us["country_code"] = plant_us["state"]
```

```python
# --- GENERATORS (capacity, fuel) ---
gen_path = "data/eia8602024/3_1_Generator_Y2024.xlsx"
gen_us = pd.read_excel(gen_path, sheet_name="Operable", header=1,
                       usecols=["Plant Code","Nameplate Capacity (MW)","Energy␣
 ↪Source 1"])
gen_us = gen_us.rename(columns={"Plant Code":"plant_id","Nameplate Capacity␣
 ↪(MW)":"cap_mw",
                                "Energy Source 1":"fuel1"})
gen_us["cap_mw"] = pd.to_numeric(gen_us["cap_mw"], errors="coerce")

# Aggregate capacity to plant; choose primary fuel by capacity share. NOTE:␣
 ↪Simplification for now.
agg_cap = gen_us.groupby("plant_id", as_index=False)["cap_mw"].sum().
 ↪rename(columns={"cap_mw":"capacity_mw"}) # type: ignore
top_fuel = (gen_us.groupby(["plant_id","fuel1"], as_index=False)["cap_mw"].sum()
                  .sort_values(["plant_id","cap_mw"], ascending=[True,False]) #␣
 ↪type: ignore
                  .drop_duplicates("plant_id")[["plant_id","fuel1"]]
                  .rename(columns={"fuel1":"fuel_primary"})) # type: ignore

# --- ENVIROASSOC abatement flags ---
# Sheet: "Emissions Control Equipment" • columns: Plant Code, Equipment Type
flags = pd.DataFrame(columns=["plant_id","has_scr","has_sncr","has_fgd"]) #␣
 ↪type: ignore
env_path = "data/eia8602024/6_1_EnviroAssoc_Y2024.xlsx"
env = pd.read_excel(env_path, sheet_name="Emissions Control Equipment",␣
 ↪header=1,
                    usecols=["Plant Code","Equipment Type"])
env = env.rename(columns={"Plant Code":"plant_id","Equipment Type":
 ↪"equip_code"})
env["equip_code"] = env["equip_code"].astype(str).str.upper().str.strip()

def any_in(series, codes):
    s = series.dropna().astype(str).str.upper().str.strip()
    return int(s.isin(codes).any())

flags = (env.groupby("plant_id")
            .agg(has_scr=("equip_code", lambda s: any_in(s, {"SR","SR-2"})),
                has_sncr=("equip_code", lambda s: any_in(s, {"SN"})),
                has_fgd=("equip_code", lambda s: any_in(s, {"SD","CD"})))
            .reset_index())

# ----- Merge to US plant table -----
plant_us = (plant_us
            .merge(agg_cap, on="plant_id", how="left")
```

```
             .merge(top_fuel, on="plant_id", how="left")
             .merge(flags,   on="plant_id", how="left"))

# Clean types/defaults + ensure one row per plant
plant_us["capacity_mw"] = plant_us["capacity_mw"].fillna(0)
plant_us["fuel_primary"] = plant_us["fuel_primary"].fillna("Unknown")
for c in ["has_scr","has_sncr","has_fgd"]:
    if c not in plant_us.columns: plant_us[c] = 0
    plant_us[c] = plant_us[c].fillna(0).astype(int)

# Drop any artefact columns if you previously ran older code
plant_us = plant_us.drop(columns=["equip","level_1"], errors="ignore")
plant_us = plant_us.drop_duplicates(subset=["plant_id"])
```

<IPython.core.display.HTML object>

[48]:
```
plant_us.head(20)
```

<IPython.core.display.HTML object>

[48]:
```
    plant_id                name state        lat         lon country  \
0          1          Sand Point    AK  55.339722 -160.497222      US
1          2        Bankhead Dam    AL  33.458665  -87.356823      US
2          3               Barry    AL    31.0069    -88.0103      US
3          4  Walter Bouldin Dam    AL  32.583889  -86.283056      US
4          7             Gadsden    AL    34.0128    -85.9708      US
5          8             Gorgas    AL  33.644344  -87.196486      US
6          9              Copper    TX    31.7569    -106.375      US
7         10       Greene County    AL    32.6017    -87.7811      US
8         11   H Neely Henry Dam    AL    33.7845    -86.0524      US
9         12            Holt Dam    AL    33.2553    -87.4495      US
10        13          Jordan Dam    AL    32.6189    -86.2548      US
11        14    Logan Martin Dam    AL  33.425878  -86.337547      US
12        15             Lay Dam    AL    32.9633    -86.5187      US
13        16          Martin Dam    AL  32.680394  -85.911442      US
14        17        Mitchell Dam    AL  32.806025  -86.444892      US
15        18      Lewis Smith Dam    AL    33.9406    -87.1077      US
16        19          Thurlow Dam    AL  32.535436  -85.887614      US
17        20           Weiss Dam    AL  34.172142  -85.753806      US
18        21           Yates Dam    AL    32.5743    -85.8901      US
19        26          E C Gaston    AL  33.244211  -86.458056      US

   country_code  capacity_mw fuel_primary  has_scr  has_sncr  has_fgd
0            AK          3.7          DFO        0         0        0
1            AL         53.9          WAT        0         0        0
2            AL       3343.5           NG        1         1        0
3            AL        225.0          WAT        0         0        0
4            AL          0.0      Unknown        0         0        0
```

5	AL	0.0	Unknown	1	0	0
6	TX	86.9	NG	0	0	0
7	AL	1288.4	NG	0	0	0
8	AL	72.9	WAT	0	0	0
9	AL	46.9	WAT	0	0	0
10	AL	100.0	WAT	0	0	0
11	AL	128.1	WAT	0	0	0
12	AL	177.0	WAT	0	0	0
13	AL	210.6	WAT	0	0	0
14	AL	170.0	WAT	0	0	0
15	AL	181.0	WAT	0	0	0
16	AL	91.0	WAT	0	0	0
17	AL	87.6	WAT	0	0	0
18	AL	50.5	WAT	0	0	0
19	AL	2034.0	NG	1	0	0

2.2.2 EU plants (EEA Large Combustion Plants)

We load **`data/eu_lcp/EEA_Industry_Dataset_LCP.xlsx`** and pick columns robustly (the LCP workbook can change sheet/column labels across releases). We harmonise to:

- `plant_id`, `name`, `lat`, `lon`, `country_code`
- `capacity_mw` (uses available capacity or **rated thermal input** as a proxy if needed)
- `fuel_primary`

Abatement flags are **not** available in LCP; we set `has_scr`, `has_sncr`, `has_fgd` to `NaN` for EU rows.

[49]:
```
# --- EU plants (deterministic from LCP_Energy_Emissions) ---
import pandas as pd, numpy as np, re

EU_DIR = "data/eu_lcp"
eu_path = f"{EU_DIR}/EEA_Industry_Dataset_LCP.xlsx"

# Read single sheet deterministically
df = pd.read_excel(eu_path, sheet_name="LCP_Energy_Emissions",␣
 ↪dtype={"LCPInspireId": str})

# Years in wide format
year_cols = [c for c in df.columns if re.fullmatch(r"\d{4}", str(c)) and 2016␣
 ↪<= int(c) <= 2023]

# Derive ISO-2 from the ID prefix like 'AT.CAED/...'
df["country_code"] = df["LCPInspireId"].str.split(".").str[0].str.upper()

# -------------------------
# Capacity (MW): take rows where featureType='LCPCharacteristics' & unit='MW'
# -------------------------
```

```python
cap_rows = df[(df["featureType"] == "LCPCharacteristics") & (df["unit"].str.
 ↪upper() == "MW")].copy()
cap_rows["capacity_mw"] = cap_rows[year_cols].max(axis=1, skipna=True)
cap = (cap_rows
       .groupby("LCPInspireId", as_index=False)
       .agg(capacity_mw=("capacity_mw","max"),
            name=("installationPartName","first"),
            lon=("Longitude","first"),
            lat=("Latitude","first"),
            country_code=("country_code","first")))

# -------------------------
# Primary fuel: pick the energy carrier (TJ) with the largest total across years
# -------------------------
FUEL_FEATURES = [
    "Coal","Lignite","OtherSolidFuels","NaturalGas",
    "LiquidFuels","OtherGases","Peat","Biomass"
]
fuel_rows = df[df["featureType"].isin(FUEL_FEATURES) & (df["unit"].str.upper()␣
 ↪== "TJ")].copy()
if not fuel_rows.empty:
    fuel_rows["energy_tj_total"] = fuel_rows[year_cols].sum(axis=1,␣
 ↪skipna=True) # type: ignore
    fuel_tot = (fuel_rows.groupby(["LCPInspireId","featureType"],␣
 ↪as_index=False)
                         .agg(energy_tj_total=("energy_tj_total","sum")))
    fuel_primary = (fuel_tot.sort_values(["LCPInspireId","energy_tj_total"],␣
 ↪ascending=[True, False]) # type: ignore
                          .drop_duplicates("LCPInspireId")
                          .rename(columns={"featureType":"fuel_primary"})
                          [["LCPInspireId","fuel_primary"]])
else:
    # If no TJ rows are present, set fuel_primary to NaN
    fuel_primary = cap[["LCPInspireId"]].assign(fuel_primary=np.nan)

# -------------------------
# Harmonise to EU plant table
# -------------------------
plant_eu = (cap.merge(fuel_primary, on="LCPInspireId", how="left")
          .rename(columns={
              "LCPInspireId":"plant_id",
              "name":"name",
              "lat":"lat",
              "lon":"lon"
          }))

plant_eu["country"] = "EU"
```

```python
plant_eu["fuel_primary"] = plant_eu["fuel_primary"].astype(object)
# Abatement flags not provided in LCP sheet
plant_eu["has_scr"] = np.nan
plant_eu["has_sncr"] = np.nan
plant_eu["has_fgd"] = np.nan

plant_eu = plant_eu[["country","country_code","plant_id","name","lat","lon",
         "capacity_mw","fuel_primary","has_scr","has_sncr","has_fgd"]].copy()
```

```
<IPython.core.display.HTML object>
```

[50]:
```python
plant_eu.head(20)
```

```
<IPython.core.display.HTML object>
```

[50]:
```
   country country_code                    plant_id  \
0       EU           AT  AT.CAED/9008390225387.PART
1       EU           AT  AT.CAED/9008390225462.PART
2       EU           AT  AT.CAED/9008390225660.PART
3       EU           AT  AT.CAED/9008390264584.PART
4       EU           AT  AT.CAED/9008390317877.PART
5       EU           AT  AT.CAED/9008390317891.PART
6       EU           AT  AT.CAED/9008390325254.PART
7       EU           AT  AT.CAED/9008390325773.PART
8       EU           AT  AT.CAED/9008390333020.PART
9       EU           AT  AT.CAED/9008390333044.PART
10      EU           AT  AT.CAED/9008390333051.PART
11      EU           AT  AT.CAED/9008390333075.PART
12      EU           AT  AT.CAED/9008390355985.PART
13      EU           AT  AT.CAED/9008390355992.PART
14      EU           AT  AT.CAED/9008390369593.PART
15      EU           AT  AT.CAED/9008390372234.PART
16      EU           AT  AT.CAED/9008390372821.PART
17      EU           AT  AT.CAED/9008390375129.PART
18      EU           AT  AT.CAED/9008390375792.PART
19      EU           AT  AT.CAED/9008390379813.PART

                          name        lat        lon  capacity_mw  \
0                  Sodakessel 3  48.183917  14.257667         98.0
1                     Gaskessel  48.183917  14.257667         66.0
2                 Kesselanlage 2  48.721250  16.278111         50.0
3                 100 to-Kessel  48.070278  14.808389         83.0
4               Laugekessel 2K7  47.975500  13.616778        100.0
5               Laugekessel 2K6  47.975500  13.616778         67.0
6              Laugekessel 2K10  47.975500  13.616778        103.0
7                 Gaskessel 1K6  47.975500  13.616778        124.0
8      RS10 Rohöldestillation 4  48.144333  16.490472        180.0
9              RS13 FCC-Anlage  48.144333  16.490472        102.0
```

```
10              RS16 Wasserstoffanlage  48.144333  16.490472         77.0
11                  RS11 Ethylenanlage  48.144333  16.490472        421.0
12                            Kessel 4  47.675750  13.108722         53.6
13                        TABA Kessel K5  47.675750  13.108722        110.0
14                            Kessel 6  48.324806  16.038500         56.0
15                Kampagnekesselanlage  48.236889  16.702389        150.0
16  Sulfatlaugenkessel 1 und Steambloc  47.217667  14.589667        244.0
17                           Kessel 11  47.134111  15.334056        133.3
18                          GuD-Anlage  47.134111  15.334056        190.0
19        Kessel K7K8 Steamblockanlage  47.996333  13.800028         62.0

      fuel_primary  has_scr  has_sncr  has_fgd
0   OtherSolidFuels      NaN       NaN      NaN
1        NaturalGas      NaN       NaN      NaN
2        NaturalGas      NaN       NaN      NaN
3        NaturalGas      NaN       NaN      NaN
4   OtherSolidFuels      NaN       NaN      NaN
5   OtherSolidFuels      NaN       NaN      NaN
6   OtherSolidFuels      NaN       NaN      NaN
7        NaturalGas      NaN       NaN      NaN
8         OtherGases      NaN       NaN      NaN
9   OtherSolidFuels      NaN       NaN      NaN
10        OtherGases      NaN       NaN      NaN
11        OtherGases      NaN       NaN      NaN
12           Biomass      NaN       NaN      NaN
13  OtherSolidFuels      NaN       NaN      NaN
14       NaturalGas      NaN       NaN      NaN
15       NaturalGas      NaN       NaN      NaN
16  OtherSolidFuels      NaN       NaN      NaN
17              Coal      NaN       NaN      NaN
18       NaturalGas      NaN       NaN      NaN
19       NaturalGas      NaN       NaN      NaN
```

2.2.3 Merged

[51]:
```
fac = pd.concat([
    plant_us[["country","country_code","plant_id","name","lat","lon",
              "capacity_mw","fuel_primary","has_scr","has_sncr","has_fgd"]],
    plant_eu
], ignore_index=True)

fac.sample(20)
```

<IPython.core.display.HTML object>

[51]:
```
     country      country_code  \
8965      US                NE
```

7352	US	CA
9480	US	MI
12155	US	TX
4332	US	WY
11588	US	GA
10251	US	OK
5339	US	AR
11364	US	OR
13284	US	TX
18819	EU	RO
13695	US	TX
855	US	MD
11274	US	IL
6612	US	CA
15172	US	IL
15918	US	NY
20422	EU	HTTPS://REGISTRY
3974	US	MA
5047	US	IA

	plant_id \
8965	61407
7352	59536
9480	61954
12155	64897
4332	55607
11588	64280
10251	62837
5339	57161
11364	64048
13284	66137
18819	RO.CAED/102GJ0311.PART
13695	66595
855	1563
11274	63954
6612	58646
15172	68130
15918	68884
20422	https://registry.gdi-de.org/id/de.nw.inspire.p…
3974	54937
5047	56811

	name	lat \
8965	Cottonwood Wind Energy Center	40.240168
7352	Coronus Adelanto West 1	34.548056
9480	Delta Solar Power I	42.7
12155	WAL3285	32.59732

```
4332                                          Foote Creek I    41.6283
11588                                     Meriwether Jackson  32.877496
10251                                  Frontier Windpower II   36.82478
5339                              White River Lock and Dam 2  35.744036
11364                                           SulusSolar29      45.46
13284                                             Zier Solar  29.350992
18819  SC COMPLEXUL ENERGETIC ROVINARI SA (SUCURSALA …  44.905864
13695                                                FTBLID2  29.575316
855                                                Crisfield  37.994134
11274                                                Mendota   41.54863
6612                                         Stateline Solar       35.6
15172                                Des Plaines 11-SLCHI211     42.015
15918                                              Glen Mary  42.128604
20422                                        Feuerung Block A   51.03765
3974               Wellesley College Central Utility Plant  42.293927
5047                                         Walnut Wind Farm    41.4517

              lon  capacity_mw fuel_primary  has_scr  has_sncr  has_fgd
8965   -98.405956         89.7          WND      0.0       0.0      0.0
7352  -117.464444          1.5          SUN      0.0       0.0      0.0
9480      -84.701          8.1          SUN      0.0       0.0      0.0
12155  -96.946914          1.2           NG      0.0       0.0      0.0
4332    -106.2013          0.0      Unknown      0.0       0.0      0.0
11588  -84.644367          3.0          SUN      0.0       0.0      0.0
10251  -97.029777        351.8          WND      0.0       0.0      0.0
5339   -91.765418          3.5          WAT      0.0       0.0      0.0
11364     -122.29          2.6          SUN      0.0       0.0      0.0
13284 -100.562028        200.4          SUN      0.0       0.0      0.0
18819   23.135615       1756.0      Lignite      NaN       NaN      NaN
13695  -95.636882         11.2           NG      0.0       0.0      0.0
855    -75.837679         11.6          DFO      0.0       0.0      0.0
11274   -89.15986          2.0          SUN      0.0       0.0      0.0
6612       -115.4        299.5          SUN      0.0       0.0      0.0
15172     -87.915          0.0      Unknown      0.0       0.0      0.0
15918  -76.278949          0.0      Unknown      0.0       0.0      0.0
20422     6.61229        855.0      Lignite      NaN       NaN      NaN
3974   -71.308111         13.9           NG      0.0       0.0      0.0
5047     -95.2383        165.2          WND      0.0       0.0      0.0
```

2.2.4 Facility structure — quick EDA

We examine distributions and composition to understand where identification strength may come from (coal/gas capacity, right tails, region mix).

[52]:
```python
import matplotlib.pyplot as plt

# Ensure numeric capacity and nonnegative
```

```python
fac['capacity_mw'] = pd.to_numeric(fac['capacity_mw'], errors='coerce').
↪fillna(0).clip(lower=0) # type: ignore

# Normalise fuel labels across US (codes) and EU (strings)
def fuel_group_map(x: object) -> str:
    s = str(x).strip().upper()
    if s in {'NATURALGAS','NG'}: return 'Gas'
    if s in␣
↪{'COAL','PC','COW','COL','BIT','SUB','ANT','LIGNITE','LIG','WC','RC'}:␣
↪return 'Coal'
    if s in {'LIQUIDFUELS','DFO','RFO','KER','JF','OIL'}: return 'Oil'
    if s in {'OTHERGASES','OBG'}: return 'Other gas'
    if s in {'OTHERSOLIDFUELS','OTHER SOLID FUELS','OSF'}: return 'Other solid'
    if s in {'BIOMASS','WDL','WDS','AB'}: return 'Biomass'
    if s in {'PEAT'}: return 'Peat'
    if s in {'NUC','NUCLEAR'}: return 'Nuclear'
    if s in {'SUN','SOLAR'}: return 'Solar'
    if s in {'WND','WIND'}: return 'Wind'
    if s in {'WAT','HYDRO'}: return 'Hydro'
    if s in {'GEO','GEOTHERMAL'}: return 'Geothermal'
    if s in {'MSW','LFG','TDF'}: return 'Waste'
    return 'Other/Unknown'

fac['fuel_group'] = fac['fuel_primary'].apply(fuel_group_map)

# --- Summary table by country ---
summary = fac.groupby('country', dropna=False)['capacity_mw'].
↪describe()[['count','mean','50%','max']].round(2)
display(summary)

# --- Capacity distribution (clip 99th to reduce distortion from mega plants)␣
↪---
plt.figure(figsize=(6,4))
fac['capacity_mw'].clip(upper=fac['capacity_mw'].quantile(0.99)).
↪plot(kind='hist', bins=40) # type: ignore
plt.title('Plant capacity distribution (clipped at 99th percentile)')
plt.xlabel('MW'); plt.ylabel('count'); plt.tight_layout(); plt.show()

# --- Composition by fuel group and country (top groups + Other) ---
top_groups = fac['fuel_group'].value_counts().head(8).index.tolist()
fac['fuel_group_top'] = np.where(fac['fuel_group'].isin(top_groups),␣
↪fac['fuel_group'], 'Other')

# counts → shares without multiindex-reset pitfalls
comp_counts = (fac.groupby(['country','fuel_group_top'], dropna=False)
                 .size()
```

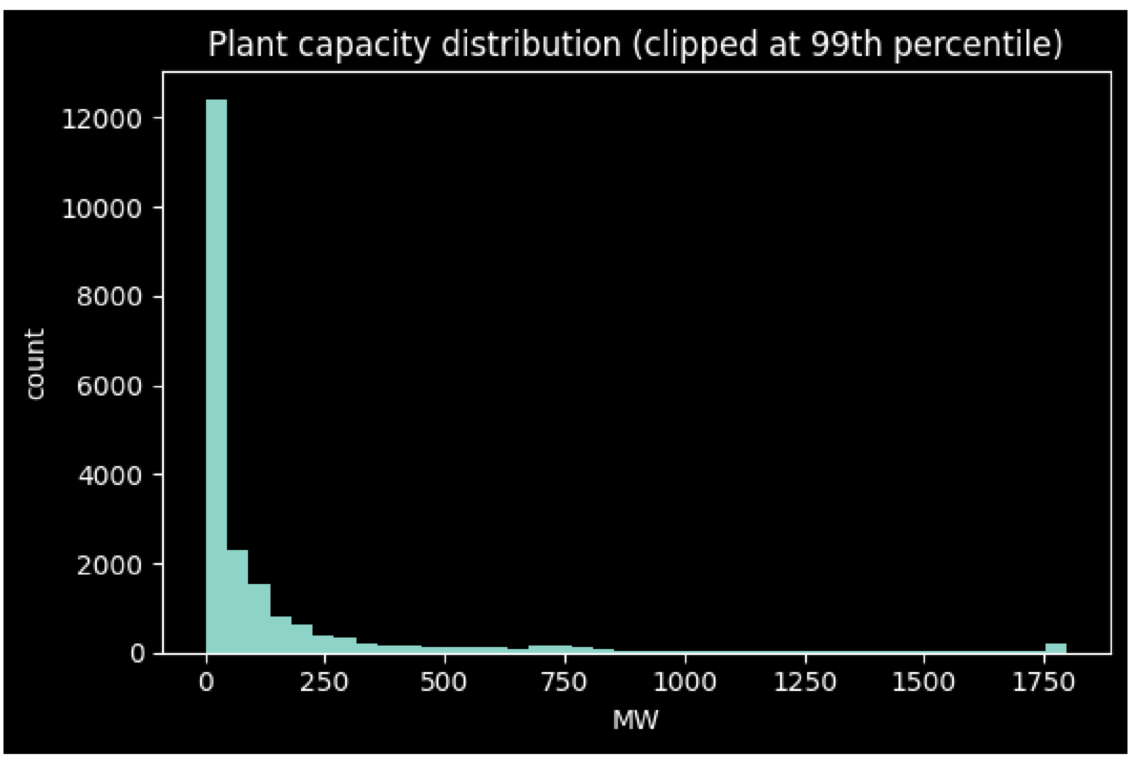
```
                 .reset_index(name='n')) # type: ignore
comp = comp_counts.assign(
    share = comp_counts['n'] / comp_counts.groupby('country')['n'].
 ↪transform('sum')
)[['country','fuel_group_top','share']]

# Pivot for a quick overview, sorted by overall prevalence
pivot = comp.pivot(index='fuel_group_top', columns='country', values='share').
 ↪fillna(0)
pivot = pivot.assign(_sum=pivot.sum(axis=1)).sort_values('_sum',␣
 ↪ascending=False).drop(columns='_sum')
display(pivot.round(3).head(15))

# --- Top 12 counts by (country, fuel_group) for a quick glance ---
cnt = (fac.groupby(['country','fuel_group'], dropna=False)
         .size()
         .reset_index(name='n') # type: ignore
         .sort_values('n', ascending=False))
display(cnt.head(12))
```

```
<IPython.core.display.HTML object>

           count    mean    50%     max
country
EU        4484.0  358.11  146.5  9611.3
US       16132.0   82.12    4.5  6809.0
```



```
country              EU     US
fuel_group_top
Gas               0.482  0.122
Solar             0.000  0.392
Other/Unknown     0.000  0.208
Other             0.128  0.033
Oil               0.106  0.053
Biomass           0.150  0.007
Coal              0.134  0.013
Hydro             0.000  0.088
Wind              0.000  0.083
```

```
   country     fuel_group     n
16      US          Solar  6331
15      US  Other/Unknown  3350
2       EU            Gas  2160
9       US            Gas  1963
11      US          Hydro  1425
18      US           Wind  1344
13      US            Oil   859
0       EU        Biomass   674
1       EU           Coal   600
4       EU      Other gas   514
3       EU            Oil   475
17      US          Waste   341
```

2.3 Load parameterised policy exposures (US + EU)

We ingest policy CSVs and derive **monthly facility exposure flags**: - `treat_any` — any applicable policy active. - `treat_cap`, `treat_standard`, `treat_lez` — class-specific active flags.

Mapping logic: 1) **Sector match**: facilities treated as `power` by default (EIA/LCP focus).
2) **Region match**: US by `state` (our `country_code`), EU by member-state `country_code` (or city for LEZ when available).
3) **Time**: active if `month >= effective_date` and, if seasonal windows exist, if the month is within `[season_start_month, season_end_month]` (wrap across year allowed).

[53]:
```
import os
import time
import requests
import pandas as pd
from typing import Dict, Iterable, List, Sequence
from pandas import Timestamp

US_PROGRAM_START = {
    "ARP":   (1, 1),  # annual
```

```
    "CSOS":  (1, 1),  # annual SO2
    "CSNOX": (5, 1),  # NOx Ozone Season starts May 1
}

API_BASE = "https://api.epa.gov/easey/facilities-mgmt/facilities/attributes"
API_KEY  = "IY73y2OB1kOtIJMFru4zA4DhHhSsSXQJKBLpOy1K"

# Canonical program codes we care about
VALID_CODES = {"ARP", "CSNOX", "CSNOXOS", "CSOSG1", "CSOSG2"}

# Friendly aliases -> one or more canonical codes
ALIAS_MAP = {
    "CSOS":   ("CSOSG1", "CSOSG2"),   # CSAPR SO2 is split in API
    "NOXOS":  ("CSNOXOS",),           # ozone season NOx
    "NOXANN": ("CSNOX",),             # annual NOx
}

# Correct program effective start dates
US_PROGRAM_START = {
    "ARP":     (1, 1),
    "CSNOX":   (1, 1),  # annual NOx
    "CSNOXOS": (5, 1),  # ozone-season NOx
    "CSOSG1":  (1, 1),
    "CSOSG2":  (1, 1),
}

def _expand_program_codes(codes: Iterable[str]) -> List[str]:
    out: List[str] = []
    for c in codes:
        c_up = str(c).upper()
        if c_up in ALIAS_MAP:
            out.extend(ALIAS_MAP[c_up])
        else:
            out.append(c_up)
    # keep only known codes, preserve order, drop dups
    seen = set()
    keep: List[str] = []
    for c in out:
        if c in VALID_CODES and c not in seen:
            keep.append(c); seen.add(c)
    return keep

def _start_date_for_policy(code, year):
    if pd.isna(year):
        return pd.NaT
    m, d = US_PROGRAM_START.get(code, (1, 1))
    return Timestamp(year=int(year), month=m, day=d)
```

```python
def _req(url: str, params: Dict, max_retries: int = 3) -> requests.Response:
    headers = {"Accept": "application/json"}
    if API_KEY:
        params = {**params, "api_key": API_KEY}
    for i in range(max_retries):
        r = requests.get(url, params=params, timeout=60, headers=headers)
        if r.status_code in (429, 500, 502, 503, 504):
            time.sleep(1.5 * (i + 1))
            continue
        if r.status_code >= 400:
            snippet = (r.text or "")[:500]
            raise requests.HTTPError(f"{r.status_code} {r.reason} for {r.url}\n{snippet}", response=r)
        return r
    r.raise_for_status() #type: ignore
    return r  #type: ignore

def _fetch_all_facility_attributes(year: int, program_code: str, per_page: int = 500) -> List[Dict]:
    page, out = 1, []
    while True:
        params = {"year": year, "programCodeInfo": program_code, "perPage": per_page, "page": page}
        r = _req(API_BASE, params)
        js = r.json() or []
        if not js:
            break
        out.extend(js)
        if len(js) < per_page:
            break
        page += 1
    return out

def build_us_policy_facility_table(
    program_codes: Iterable[str] = ("ARP", "CSNOXOS", "CSOS"),
    years: Iterable[int] = range(2015, 2026),
    save_raw_identification: bool = True,
    out_dir: str = "data/out/raw",
    restrict_to_egus: bool = True,  # <-- new
) -> pd.DataFrame:
    os.makedirs(out_dir, exist_ok=True)

    expanded_codes: Sequence[str] = _expand_program_codes(program_codes)
    frames: List[pd.DataFrame] = []

    for code in expanded_codes:
```

```
        for y in years:
            rows = _fetch_all_facility_attributes(y, code)
            if not rows:
                continue
            df = pd.DataFrame.from_records(rows)
            df["policy_code"] = code
            df["year"] = y
            frames.append(df)

    raw = pd.concat(frames, ignore_index=True) if frames else pd.DataFrame()
    if save_raw_identification and not raw.empty:
        raw.to_csv(os.path.join(out_dir, "us_facility_attributes_by_year.csv.
↪gz"),
                   index=False, compression="gzip")

    if raw.empty:
        return pd.
↪DataFrame(columns=["facilityId","policy_code","earliest_year","facilityName","stateCode","e
↪# type: ignore

    # scope to EGUs (power plants)
    if restrict_to_egus:
        cat = raw.get("sourceCategory")
        oris = raw.get("orisCode")
        # Keep Electric Utility, or anything with an ORIS code (robust to null/
↪odd categories)
        mask = (cat == "Electric Utility") | (oris.notna() if oris is not None␣
↪else False)
        scoped = raw.loc[mask].copy()
        # write a quick profile for QC
        (raw.assign(_scoped=mask)
            .groupby(["policy_code","_scoped","sourceCategory"], dropna=False)
            .size().rename("n").reset_index() # type: ignore
            .to_csv(os.path.join(out_dir, "us_scope_profile.csv"), index=False))
    else:
        scoped = raw

    # --------- aggregate to one row per (facility x policy) ----------
    needed = ["facilityId", "policy_code", "year"]
    keep_meta = [c for c in␣
↪("facilityName","stateCode","orisCode","epaRegion","county","sourceCategory")␣
↪if c in scoped.columns]
    small = scoped[[c for c in needed + keep_meta if c in scoped.columns]].
↪copy()

    agg_dict = {"year": "min"}
```

```
    for c in keep_meta:
        agg_dict[c] = "first"

    eda = (small
           .groupby(["facilityId","policy_code"], as_index=False)
           .agg(agg_dict)
           .rename(columns={"year":"earliest_year"})) # type: ignore

    eda["country"] = "US"
    if "stateCode" in eda.columns and "country_code" not in eda.columns:
        eda["country_code"] = eda["stateCode"]

    # exact effective date per program (Jan 1 for ARP/CSNOX/CSOS groups; May 1␣
↪for ozone-season NOx)
    eda["effective_date"] = eda.apply(lambda r:␣
↪_start_date_for_policy(r["policy_code"], r["earliest_year"]), axis=1)
    return eda
us_policies = build_us_policy_facility_table()
display(us_policies.head(10))
display(us_policies.policy_code.value_counts())
```

```
<IPython.core.display.HTML object>

   facilityId policy_code  earliest_year    facilityName stateCode  epaRegion  \
0           3         ARP           2015           Barry        AL          4
1           3     CSNOXOS           2015           Barry        AL          4
2           3      CSOSG2           2017           Barry        AL          4
3           7         ARP           2015         Gadsden        AL          4
4           7     CSNOXOS           2015         Gadsden        AL          4
5           7      CSOSG2           2017         Gadsden        AL          4
6           8         ARP           2015          Gorgas        AL          4
7           8     CSNOXOS           2015          Gorgas        AL          4
8           8      CSOSG2           2017          Gorgas        AL          4
9           9     CSNOXOS           2015  Copper Station        TX          6

           county    sourceCategory country country_code effective_date
0   Mobile County  Electric Utility      US           AL     2015-01-01
1   Mobile County  Electric Utility      US           AL     2015-05-01
2   Mobile County  Electric Utility      US           AL     2017-01-01
3   Etowah County  Electric Utility      US           AL     2015-01-01
4   Etowah County  Electric Utility      US           AL     2015-05-01
5   Etowah County  Electric Utility      US           AL     2017-01-01
6   Walker County  Electric Utility      US           AL     2015-01-01
7   Walker County  Electric Utility      US           AL     2015-05-01
8   Walker County  Electric Utility      US           AL     2017-01-01
9  El Paso County  Electric Utility      US           TX     2015-05-01

policy_code
```

```
ARP        1209
CSNOXOS     839
CSOSG2      740
CSOSG1       32
Name: count, dtype: int64
```

[56]:
```python
# --- EU ETS installation-level exposure via pyeutl.ziploader (EUETS.INFO␣
↪extracts) ---

import os
import pandas as pd

EU_OUT = "data/out/raw"
os.makedirs(EU_OUT, exist_ok=True)

EUETS_ZIP = "data/eutl_2024_202410/eutl_2024_202410.zip"  # your path

# Stationary ETS activities (keep). Exclude aviation=10, maritime=50,␣
↪opted-in=99, effort sharing=1000.
# Also exclude CCS chain (45-47) unless you explicitly want it.
_ALLOWED_ACTIVITY_IDS = {
    # Phase 3/4 style IDs
    20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,
    # Legacy installation-class IDs
    1,2,3,4,5,6,7,8,9
}

def _std_install_cols(df: pd.DataFrame) -> pd.DataFrame:
    out = df.copy()
    if "installation_id" not in out.columns and "id" in out.columns:
        out = out.rename(columns={"id": "installation_id"})
    if "installation_name" not in out.columns and "name" in out.columns:
        out = out.rename(columns={"name": "installation_name"})
    if "country_code" not in out.columns:
        if "country" in out.columns:
            out["country_code"] = out["country"].astype(str).str.upper()
        elif "registry" in out.columns:
            out["country_code"] = out["registry"].astype(str).str.upper()
        elif "country_id" in out.columns:
            out["country_code"] = out["country_id"].astype(str).str.upper()
        else:
            out["country_code"] = pd.NA
    return out

def _ensure_installation_id(df: pd.DataFrame) -> pd.DataFrame:
    out = df.copy()
    if "installation_id" not in out.columns and "id" in out.columns:
```

```
        out = out.rename(columns={"id":"installation_id"})
    return out

def _first_txn_year_from_surr_alloc(euets_zip: str) -> pd.DataFrame:
    """
    OPTIONAL: earliest transaction year suggesting exposure via surrender/alloc/
↪auction.
    Uses transaction & account tables to map to installations.
    """
    from pyeutl import ziploader
    inst = ziploader.get_installations(euets_zip)
    acc  = ziploader.get_accounts(euets_zip, df_installation=inst)  # attaches␣
↪installation info
    txn  = ziploader.get_transactions(euets_zip, df_account=acc)

    # Prefer supplementary codes for semantic signal:
    # 2=Allowance surrender, 35/36=Allocation (aviation/general), 37=Auction␣
↪delivery,
    # 30/31=Issuance aviation/general, 53=Allowance allocation (older label)
    keep_supp = {2,30,31,35,36,37,53}
    if "transactionTypeSupplementary_id" in txn.columns:
        txn = txn[txn["transactionTypeSupplementary_id"].isin(keep_supp)]

    # Use either acquiring or transferring installation id when present
    install_cols = [c for c in txn.columns if c.endswith("Installation_id")]
    if not install_cols:
        return pd.DataFrame(columns=["installation_id","first_txn_year"]) #type:
↪ ignore
    txn["installation_id"] = txn.get("acquiringInstallation_id").fillna(txn.
↪get("transferringInstallation_id"))
    txn = txn.dropna(subset=["installation_id"]).copy()

    # derive year
    if "date" in txn.columns:
        txn["year"] = pd.to_datetime(txn["date"], errors="coerce").dt.year.
↪astype("Int64")
    else:
        return pd.DataFrame(columns=["installation_id","first_txn_year"]) #type:
↪ ignore

    out = (txn.dropna(subset=["year"])
              .groupby("installation_id", as_index=False)
              .agg(first_txn_year=("year","min")))
    return out

def build_eu_ets_installation_exposure(
```

```python
    euets_zip: str = EUETS_ZIP,
    save_raw: bool = True,
    allowed_activity_ids = _ALLOWED_ACTIVITY_IDS,
    include_transaction_signal: bool = False,
) -> pd.DataFrame:
    from pyeutl import ziploader

    # --- Load raw tables
    inst = ziploader.get_installations(euets_zip)
    comp = ziploader.get_compliance(euets_zip, create_id=False)

    # Optional persistence for later, richer matching/QA
    if save_raw:
        inst.to_csv(os.path.join(EU_OUT, "euets_installations.csv.gz"),␣
↪index=False, compression="gzip")
        comp.to_csv(os.path.join(EU_OUT, "euets_compliance.csv.gz"),␣
↪index=False, compression="gzip")

    # --- Standardize keys/labels
    inst = _std_install_cols(inst)
    comp = _ensure_installation_id(comp)

    # Filter to stationary ETS activities
    if "activity_id" in inst.columns:
        inst = inst[inst["activity_id"].isin(set(allowed_activity_ids))].copy()␣
↪#type: ignore

    # --- First observed ETS activity = first compliance year
    if "year" in comp.columns:
        comp["year"] = pd.to_numeric(comp["year"], errors="coerce").
↪astype("Int64")     #type: ignore
    first_comp = comp.groupby("installation_id", as_index=False).
↪agg(first_year=("year","min"))

    expo = inst.merge(first_comp, on="installation_id", how="left") #type:␣
↪ignore

    # Optional: fold in earliest transaction year signal (surrender/alloc/
↪auction)
    if include_transaction_signal:
        tmin = _first_txn_year_from_surr_alloc(euets_zip)
        expo = expo.merge(tmin, on="installation_id", how="left")
        expo["effective_year"] = expo[["first_year","first_txn_year"]].
↪min(axis=1)
    else:
        expo["effective_year"] = expo["first_year"]
```

```
    expo["effective_date"] = expo["effective_year"].map(
    lambda y: pd.Timestamp(year=int(y), month=1, day=1) if pd.notna(y) else pd.
↪NaT)

    # --- Compact EDA view (one row / installation)
    keep =␣
↪["installation_id","installation_name","country_code","effective_year","effective_date",
            "activity","activityCategory","nace","naceCategory","sector"]
    keep = [c for c in keep if c in expo.columns]

    # include coords if present (names vary by dump)
    for c in␣
↪("lat","latitude","latitudeWgs84","lon","longitude","longitudeWgs84"):
        if c in expo.columns:
            keep.append(c)

    eda = expo[keep].drop_duplicates(subset=["installation_id"]).copy() #type:␣
↪ignore
    eda["policy_code"]  = "ETS"
    eda["policy_class"] = "cap"
    eda["country"]      = "EU"

    if save_raw:
        eda.to_csv(os.path.join(EU_OUT, "euets_installation_exposure.csv.gz"),␣
↪index=False, compression="gzip")
    return eda


eu_ets = build_eu_ets_installation_exposure(include_transaction_signal=False)
display(eu_ets.head(10), eu_ets.country_code.value_counts().head(10))
```

```
<IPython.core.display.HTML object>

  installation_id                   installation_name country_code  \
0          AT_106              Glanzstoff St. Pölten      AUSTRIA
1           AT_83         CMOÖ GuD Anlage Laakirchen      AUSTRIA
2          AT_118                 Borealis Schwechat      AUSTRIA
3            AT_2  Breitenfelder Edelstahl Mitterdorf      AUSTRIA
4            AT_1                    Calmit Bad Ischl      AUSTRIA
5           AT_25              LAT Nitrogen Linz GmbH      AUSTRIA
6           AT_36            Salzburg AG LKH Salzburg      AUSTRIA
7           AT_65             Wienerberger Gleinstätten      AUSTRIA
8           AT_35          Salzburg AG HW Süd Salzburg      AUSTRIA
9            AT_6                 Novartis Werk Kundl      AUSTRIA

   effective_year effective_date  \
0            2005     2005-01-01
```

```
1           2005     2005-01-01
2           2005     2005-01-01
3           2005     2005-01-01
4           2005     2005-01-01
5           2005     2005-01-01
6           2005     2005-01-01
7           2005     2005-01-01
8           2005     2005-01-01
9           2005     2005-01-01

                                          activity activityCategory  \
0  Combustion installations with a rated thermal …       Combustion
1                              Combustion of fuels       Combustion
2                     Production of bulk chemicals        Chemicals
3                   Production of pig iron or steel            Metal
4  Production of lime, or calcination of dolomite…      Cement/Lime
5                              Combustion of fuels       Combustion
6  Combustion installations with a rated thermal …       Combustion
7                          Manufacture of ceramics   Glass/Ceramics
8  Combustion installations with a rated thermal …       Combustion
9                              Combustion of fuels       Combustion

                                              nace  \
0                     Manufacture of man-made fibres
1  Electric power generation, transmission and di…
2           Manufacture of plastics in primary forms
3  Manufacture of basic iron and steel and of fer…
4                    Manufacture of lime and plaster
5  Manufacture of fertilisers and nitrogen compounds
6                  Steam and air conditioning supply
7  Manufacture of bricks, tiles and construction …
8                          Production of electricity
9      Manufacture of basic pharmaceutical products

                                      naceCategory policy_code policy_class  \
0  Manufacturing: Refineries, chemicals, and  pha…         ETS          cap
1                     Energy: Electricity generation         ETS          cap
2  Manufacturing: Refineries, chemicals, and  pha…         ETS          cap
3               Manufacturing: Metals and machineries         ETS          cap
4           Manufacturing: Glas, ceramic, and stones         ETS          cap
5  Manufacturing: Refineries, chemicals, and  pha…         ETS          cap
6         Energy: Steam and air conditioning supply         ETS          cap
7           Manufacturing: Glas, ceramic, and stones         ETS          cap
8                     Energy: Electricity generation         ETS          cap
9  Manufacturing: Refineries, chemicals, and  pha…         ETS          cap

  country
0      EU
```

```
1       EU
2       EU
3       EU
4       EU
5       EU
6       EU
7       EU
8       EU
9       EU

country_code
GERMANY           2680
FRANCE            1588
ITALY             1585
SPAIN             1479
UNITED KINGDOM    1468
POLAND            1097
SWEDEN             933
NETHERLANDS        659
BELGIUM            483
FINLAND            461
Name: count, dtype: int64
```

2.4 Policy → monthly exposure logic

From each policy identification table we create facility×**month** flags:

- `treat_any` — active if any tracked policy is "on" in that month.
- `treat_cap`, `treat_standard`, `treat_lez` — class-specific flags (currently we populate **cap** for ARP/CSAPR/EU ETS; `standard/lez` reserved for MATS/IED/LEZ later).
- Seasonality: policies with seasonal windows (e.g., **CSAPR NOx Ozone-Season**) are active **only** within their months (May–Sept), repeating annually after the start year.

We keep the per-policy detail too (so you can run policy-specific event studies or collapse to any aggregate).

[57]:
```
# Expand US + EU policy coverages to MONTHLY facility-level flags (2015-2025)

from pandas import Timestamp

# Month index we care about
MONTHS = pd.DataFrame({"month": pd.period_range("2015-01", "2025-12", freq="M").
 ↪to_timestamp()})

# Seasonal windows by policy (month numbers)
SEASONAL = {
    "CSNOXOS": {5,6,7,8,9},  # ozone season
    # others are annual
}
```

```
def _is_seasonal_active(policy_code: str, month: int) -> bool:
    s = SEASONAL.get(policy_code, None)
    return True if s is None else (month in s)

# ---------- US monthly ----------
us_src = us_policies.copy()
us_src["effective_date"] = pd.to_datetime(us_src["effective_date"], errors="coerce")
us_long = (us_src.merge(MONTHS, how="cross")
                 .query("month >= effective_date"))

# apply seasonality
us_long = us_long[
    us_long.apply(lambda r: _is_seasonal_active(str(r["policy_code"]), int(r["month"].month)), axis=1)
].copy()

us_long["policy_class"] = "cap"
us_long["treat_cap"] = 1
us_long["treat_any"] = 1
us_long["country"] = "US"
us_long.rename(columns={"facilityId":"plant_id"}, inplace=True)  # neutral name for 'facility key' # type: ignore

us_monthly = (us_long[["plant_id","country","country_code","policy_code","policy_class","month","treat_c
              .sort_values(["plant_id","month","policy_code"])) # type: ignore

# ---------- EU monthly ----------
eu_src = eu_ets.copy()
eu_src["effective_date"] = pd.to_datetime(eu_src["effective_date"], errors="coerce")
eu_long = (eu_src.merge(MONTHS, how="cross")
                 .query("month >= effective_date"))

eu_long["policy_code"] = "ETS"
eu_long["policy_class"] = "cap"
eu_long["treat_cap"] = 1
eu_long["treat_any"] = 1
eu_long["country"] = "EU"
eu_long.rename(columns={"installation_id":"plant_id"}, inplace=True)

eu_monthly = (eu_long[["plant_id","country","country_code","policy_code","policy_class","month","treat_c
              .sort_values(["plant_id","month"])) # type: ignore
```

```python
# ---------- Combine ----------
policy_monthly = pd.concat([us_monthly, eu_monthly], ignore_index=True)
display(policy_monthly.sample(12))
print("rows:", f"{len(policy_monthly):,}")
print(policy_monthly.groupby(["country","policy_code"]).size().to_frame("rows").
 ↪head(10))
```

```
<IPython.core.display.HTML object>

         plant_id country    country_code policy_code policy_class  \
1960672    NL_382      EU     NETHERLANDS         ETS          cap
355277     BE_248      EU         BELGIUM         ETS          cap
1975229     NL_78      EU     NETHERLANDS         ETS          cap
321910     BE_125      EU         BELGIUM         ETS          cap
1696534 IT_202162      EU           ITALY         ETS          cap
878720      EE_14      EU         ESTONIA         ETS          cap
606976  DE_202005      EU         GERMANY         ETS          cap
1426223 GB_210513      EU  UNITED KINGDOM         ETS          cap
2316008    SE_509      EU          SWEDEN         ETS          cap
1615733     HU_49      EU         HUNGARY         ETS          cap
141015       7155      US              IA      CSOSG2          cap
1444435    GB_295      EU  UNITED KINGDOM         ETS          cap

             month  treat_cap  treat_any
1960672 2020-04-01          1          1
355277  2019-05-01          1          1
1975229 2023-05-01          1          1
321910  2021-10-01          1          1
1696534 2019-10-01          1          1
878720  2024-08-01          1          1
606976  2017-04-01          1          1
1426223 2021-11-01          1          1
2316008 2019-08-01          1          1
1615733 2018-05-01          1          1
141015  2025-11-01          1          1
1444435 2021-07-01          1          1

rows: 2,401,753
                        rows
country policy_code
EU      ETS          2118204
US      ARP           155124
        CSNOXOS        46105
        CSOSG1          3456
        CSOSG2         78864
```

[58]:
```python
# join keys to facilities (US): ORIS -> EIA plant_id, when available
# Many EASEY rows include orisCode. If present, we expose plant_id for an easy␣
↪merge to plant_us / fac.

if "orisCode" in us_policies.columns:
    oris_map = (us_policies[["facilityId","orisCode"]]
                .dropna().drop_duplicates()
                .rename(columns={"facilityId":"plant_id"})) # type: ignore
    policy_monthly = policy_monthly.merge(oris_map, on="plant_id", how="left")
    # EIA plant_id is numeric; coerce ORIS to int if clean
    if "orisCode" in policy_monthly and policy_monthly["orisCode"].notna().
↪any(): # type: ignore
        policy_monthly["plant_id"] = pd.to_numeric(policy_monthly["orisCode"],␣
↪errors="coerce").astype("Int64") # type: ignore

# Example: preview a merged slice for US rows where we have plant_id
cols = ["plant_id","country","country_code","policy_code","month","treat_cap"]
display(policy_monthly.query("country=='US' and plant_id.notna()")[cols].
↪sample(10))
```

```
<IPython.core.display.HTML object>

       plant_id country country_code policy_code      month  treat_cap
208611    55234      US           MO     CSNOXOS 2018-08-01          1
262736    56569      US           CA         ARP 2015-03-01          1
117104     6017      US           IL         ARP 2016-06-01          1
171656     8102      US           OH      CSOSG2 2023-09-01          1
251979    56046      US           CA         ARP 2019-10-01          1
243144    55714      US           AR     CSNOXOS 2016-08-01          1
55862      2038      US           MN         ARP 2022-08-01          1
272503    58005      US           TX         ARP 2022-09-01          1
240240    55667      US           PA         ARP 2021-11-01          1
75708      2723      US           NC         ARP 2020-02-01          1
```

2.4.1 Notes on linking policy → facility master

- **US**: When `orisCode` is present in the EASEY payload we create `plant_id = orisCode`, which merges 1:1 to **EIA** `plant_id`. If an ORIS is missing, keep the `plant_id` (CAMPD facilityId) and join later via a name/geo mapping if needed.
- **EU**: ETS installation IDs (e.g., `AT_106`) do **not** equal EEA-LCP IDs (e.g., `AT.CAED/...PART`). A robust join needs fuzzy/name + geo proximity (e.g., 1–2 km). For now we keep the ETS monthly table at **installation level** (`plant_id`) and merge spatially in a later step.

2.4.2 EIA-860M operability → used to mask monthly exposures

We parse monthly EIA-860M generator snapshots, build a plant×month operability table, and **zero out policy flags** for US plants/months that are not operable. EU rows are left unchanged (860M is US-only).

Masking rule: if `is_operable==0` for a (plant_id, month), then `treat_* = 0` for that row; if operability is unknown for that month, we leave flags as-is.

[59]:
```
# --------- 860M loader (snapshot-by-file → plant×month operability) ----------
import datetime as dt
import re
from pathlib import Path
import pandas as pd
import numpy as np

FOSSIL =␣
↪{"NG","DFO","RFO","KER","JF","PC","COW","COL","BIT","SUB","LIG","ANT","WC","RC"}

def month_from_name(s: str):
    m = s.lower()
    mm = {'jan':1,'feb':2,'mar':3,'apr':4,'may':5,'jun':6,'jul':7,'aug':8,'sep':
↪9,'sept':9,'oct':10,'nov':11,'dec':12}
    for k,v in mm.items():
        if k in m: return v
    return None

def ym_from_filename(p: Path):
    y = None; m = month_from_name(p.stem)
    y_match = re.search(r"(20\d{2})", p.stem)
    if y_match: y = int(y_match.group(1))
    if y and m: return pd.Timestamp(year=y, month=m, day=1)
    return None

def load_860m_month(p: Path) -> pd.DataFrame:
    xls = pd.ExcelFile(p)
    df = pd.read_excel(xls, sheet_name="Operating", header=2)

    plant_col = "Plant ID"
    cap_col   = "Nameplate Capacity (MW)"
    fuel_col  = "Energy Source Code"

    df = df[[plant_col, cap_col, fuel_col]].copy()
    df.columns = ["plant_id","cap_mw","fuel1"]
    df["cap_mw"] = pd.to_numeric(df["cap_mw"], errors="coerce")
    df["fuel1"] = df["fuel1"].astype(str).str.upper().str.strip()

    ym = ym_from_filename(p)
    if ym is None:
        # best-effort from a month column if present
        for cand in ["report month","data month","month"]:
            if cand in df:
                try:
```

```
                    ym = pd.to_datetime(df[cand].iloc[0]).to_period("M").
↪to_timestamp() # type: ignore
                    break
                except Exception:
                    pass
        if ym is None:
            raise ValueError(f"Could not infer year-month from file name or␣
↪columns: {p.name}")

    df["ym"] = ym
    df["is_fossil"] = df["fuel1"].isin(FOSSIL) # type: ignore
    df["cap_mw_fossil"] = df["cap_mw"].where(df["is_fossil"], 0) # type: ignore

    agg = (df.groupby(["plant_id","ym"], as_index=False)
             .agg(operable_capacity_mw=("cap_mw","sum"),
                  operable_capacity_mw_fossil=("cap_mw_fossil","sum"),
                  is_operable=("cap_mw", lambda s: int(pd.notna(s).any()))))
    return agg # type: ignore

# Discover files: primary in data/eia860m, but also accept any uploaded in /mnt/
↪data
e860m_dir = Path("data/eia860m")
files = []
if e860m_dir.exists():
    files += sorted([p for p in e860m_dir.glob("*.xlsx")])

# example extra upload path (optional)
up = Path("/mnt/data/july_generator2025.xlsx")
if up.exists():
    files.append(up)

op_parts = []
for p in files:
    try:
        op_parts.append(load_860m_month(p))
    except Exception as e:
        print(f"[860M] Skipped {p.name}: {e}")
op_us = (pd.concat(op_parts, ignore_index=True)
         if op_parts else
         pd.
↪DataFrame(columns=["plant_id","ym","operable_capacity_mw","operable_capacity_mw_fossil","is
↪# type: ignore
op_us.head()
```

```
<IPython.core.display.HTML object>
```

[59]:
```
   plant_id         ym  operable_capacity_mw  operable_capacity_mw_fossil  \
0       1.0 2025-07-01                   3.7                          2.7
1       2.0 2025-07-01                  53.9                          0.0
2       3.0 2025-07-01                3343.5                       3343.5
3       4.0 2025-07-01                 225.0                          0.0
4       9.0 2025-07-01                  86.9                         86.9

   is_operable
0            1
1            1
2            1
3            1
4            1
```

[60]:
```
# --------- Mask the monthly policy flags using 860M (US only) ----------
# Assumes `policy_monthly` exists from the US+EU policy build.
# If your policy frame uses 'month', we align to that; otherwise create it.

pm = policy_monthly.copy()
if "month" not in pm.columns:
    # earlier cells used 'month' already; this is just a safeguard
    pm = pm.rename(columns={"ym":"month"})
pm["month"] = pd.to_datetime(pm["month"])

# 860M uses 'ym' (start-of-month) - align to 'month'
op = op_us.rename(columns={"ym":"month"}).copy()
op["month"] = pd.to_datetime(op["month"])

# We can only mask US rows **with** an EIA plant_id.
# Earlier US policy build adds ORIS→plant_id when present; if not present, we␣
↪leave flags as-is.
cols_flags = [c for c in ["treat_any","treat_cap","treat_standard","treat_lez"]␣
↪if c in pm.columns]

pm_us = pm.query("country=='US'").copy()
pm_eu = pm.query("country!='US'").copy()

# only rows where we have a usable plant_id
has_pid = pm_us["plant_id"].notna()
pm_us_pid = pm_us.loc[has_pid].copy()
pm_us_nopid = pm_us.loc[~has_pid].copy()  # cannot be masked

pm_us_pid = pm_us_pid.merge(op[["plant_id","month","is_operable"]],
                            on=["plant_id","month"], how="left")

for c in cols_flags:
    pm_us_pid[c] = np.where(pm_us_pid["is_operable"]==0, 0, pm_us_pid[c])
```

```python
# Combine back
policy_monthly = pd.concat([pm_us_pid.drop(columns=["is_operable"]),
                            pm_us_nopid,
                            pm_eu], ignore_index=True)

# simple coverage message
if not op.empty:
    cov = (pm_us_pid["is_operable"].notna()
           .groupby(pm_us_pid["month"]).mean())
    if (cov>0).any():
        first_cov = cov[cov>0].index.min().strftime('%Y-%m')
        last_cov  = cov[cov>0].index.max().strftime('%Y-%m')
        print(f"[860M] Operability coverage present for {first_cov} →␣
↪{last_cov} (share varies by month).")
else:
    print("[860M] No operability files found or parsed; policy flags are␣
↪unmasked.")

display(policy_monthly.sample(10))

# For **fossil-only masking**, replace the binary `is_operable` rule with a␣
↪threshold on `operable_capacity_mw_fossil` (e.g., set flags to zero when␣
↪fossil MW == 0). The `op_us` table above already carries both totals.
```

```
<IPython.core.display.HTML object>

[860M] Operability coverage present for 2025-07 → 2025-07 (share varies by
month).

        plant_id country   country_code policy_code policy_class      month  \
1282614   FR_504      EU         FRANCE         ETS          cap 2022-06-01
772929    DE_682      EU        GERMANY         ETS          cap 2019-09-01
1440518   GB_268      EU UNITED KINGDOM         ETS          cap 2025-02-01
1941147   NL_249      EU    NETHERLANDS         ETS          cap 2021-03-01
1680848   IT_144      EU          ITALY         ETS          cap 2021-08-01
538144   DE_1498      EU        GERMANY         ETS          cap 2023-04-01
1315728    FR_74      EU         FRANCE         ETS          cap 2020-12-01
548570   DE_1570      EU        GERMANY         ETS          cap 2023-02-01
271097     57839      US             NJ      CSOSG2          cap 2025-10-01
1761941   IT_357      EU          ITALY         ETS          cap 2025-05-01

         treat_cap  treat_any
1282614          1          1
772929           1          1
1440518          1          1
1941147          1          1
1680848          1          1
```

```
538144            1          1
1315728           1          1
548570            1          1
271097            1          1
1761941           1          1
```

2.4.3 Policy exposure EDA

We chart the **share of facilities treated** over time. If EIA-860M coverage exists for a month, we compute shares **among operable plant-months** only; otherwise we fall back to all rows. We also show a quick **operability coverage** plot to visualise which months are informed by 860M.

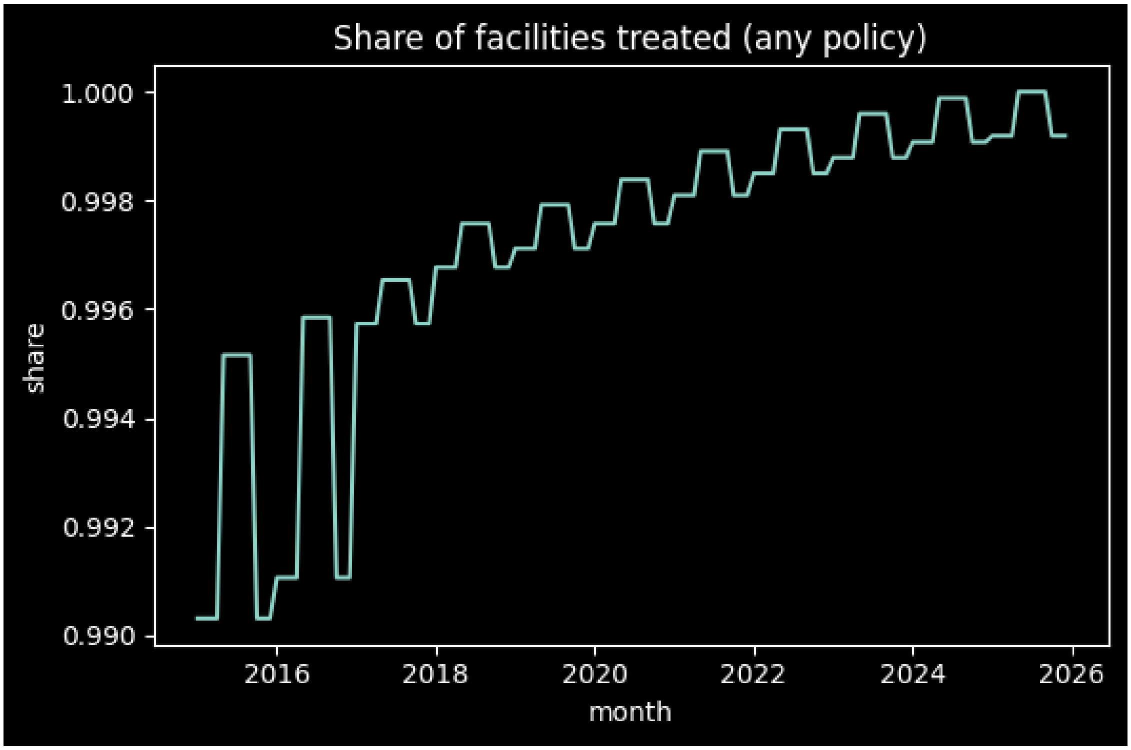
[63]:
```
# 1) Collapse policy_monthly to one row per plant-month (any policy active = 1)
pm_any = (policy_monthly
          .groupby(['country','country_code','plant_id','month'],␣
 ↪as_index=False)
          .agg(treat_any=('treat_any','max'),
               treat_cap=('treat_cap','max')))

# 2) Build a complete plant×month grid for the analysis window
MONTHS = pd.DataFrame({'month': pd.period_range('2015-01','2025-12', freq='M').
 ↪to_timestamp()})
plants = pm_any[['country','country_code','plant_id']].drop_duplicates()
panel = (plants.merge(MONTHS, how='cross')
               .merge(pm_any, on=['country','country_code','plant_id','month'],␣
 ↪how='left')
               .fillna({'treat_any':0, 'treat_cap':0})
               .assign(treat_any=lambda d: d['treat_any'].astype(int),
                       treat_cap=lambda d: d['treat_cap'].astype(int)))

# 3) Now compute monthly shares properly
share_treated = panel.groupby('month', as_index=False)['treat_any'].mean()
plt.figure(figsize=(6,4))
plt.plot(share_treated['month'], share_treated['treat_any'])
plt.title('Share of facilities treated (any policy)')
plt.ylabel('share'); plt.xlabel('month'); plt.tight_layout(); plt.show()

by_class = panel.groupby('month')[['treat_cap']].mean()
display(by_class.tail())
```

```
<IPython.core.display.HTML object>
```




```
             treat_cap
month
2025-08-01    1.000000
2025-09-01    1.000000
2025-10-01    0.999192
2025-11-01    0.999192
2025-12-01    0.999192
```

2.5 TODO: Satellite outcome and geographic controls

We demonstrate **monthly NO time series** near a sample of facilities (10 km buffers; Google Earth Engine). We later join these to the **policy panel** to compare treated vs not-yet-treated trajectories.

[12]:
```python
import ee, geemap, datetime as dt

ee.Authenticate(); ee.Initialize()

s5p = ee.ImageCollection('COPERNICUS/S5P/NRTI/L3_NO2')  # daily # type: ignore

def month_range(start='2019-01', end='2021-12'):
    d0 = dt.datetime.strptime(start, '%Y-%m'); d1 = dt.datetime.strptime(end, '%Y-%m')
    out=[]
```

```
    while d0<=d1:
        out.append((d0.year,d0.month))
        d0 = (d0 + pd.offsets.MonthBegin(1)) # type: ignore
    return out

def no2_month_mean(lat,lon,year,month,buffer_km=10):
    geom = ee.Geometry.Point([lon,lat]).buffer(buffer_km*1000) # type: ignore
    start=ee.Date.fromYMD(year,month,1); end=start.advance(1,'month') # type:␣
 ↪ignore
    img = s5p.filterDate(start,end).select('NO2_column_number_density').mean()␣
 ↪# type: ignore
    return img.reduceRegion(ee.Reducer.mean(), geom, scale=10000).
 ↪get('NO2_column_number_density') # type: ignore

# Sample a subset aligned with policy panel facilities to enable joins
#fac_ids = pol_panel['plant_id'].drop_duplicates().sample(min(30,␣
 ↪pol_panel['plant_id'].nunique()), random_state=42)
#fac_sample = fac.merge(fac_ids.to_frame(name='plant_id'), on='plant_id',␣
 ↪how='inner')

records=[]
#for _,r in fac_sample.iterrows():
#    for (y,m) in month_range('2019-01','2021-12'):
#        records.append({'plant_id':r.plant_id,'name':r.name,'lat':r.lat,'lon':
 ↪r.lon,'ym':f'{y}-{m:02d}',
#                         'no2_mean': no2_month_mean(r.lat,r.lon,y,m)})

fc = ee.FeatureCollection([ee.Feature(None,x) for x in records]) # type: ignore
ts = geemap.ee_to_df(fc)
#ts.to_csv(OUT/'no2_timeseries_sample.csv', index=False)
ts.head()
```

<IPython.core.display.HTML object>

[12]:
```
Empty DataFrame
Columns: []
Index: []
```

2.5.1 Join NO series with policy exposure

We merge the monthly NO near facilities with the corresponding **policy flags** to visualise treated vs not-yet-treated trajectories. This is **purely descriptive** and not a causal estimate, but it surfaces pre-trends, seasonal differences, and potential effect windows.

[ ]:
```
tsj = ts.merge(pol_panel, on=['plant_id','ym'], how='left')
tsj[['treat_any','treat_cap','treat_standard','treat_lez']] =␣
 ↪tsj[['treat_any','treat_cap','treat_standard','treat_lez']].fillna(0)
```

```
# Descriptive: treated vs not-yet-treated
agg = tsj.groupby(['ym','treat_any'])['no2_mean'].mean().reset_index()
plt.figure(figsize=(7,4))
for k,g in agg.groupby('treat_any'):
    label = 'treated' if k==1 else 'not yet treated'
    plt.plot(g['ym'], g['no2_mean'], label=label)
plt.title('Average NO  near facilities: treated vs not yet treated␣
 ↪(descriptive)')
plt.xlabel('month'); plt.ylabel('NO  column (mol/m²)'); plt.legend(); plt.show()

display(tsj.head())
```

2.5.2 NO trends for exemplar facilities

We plot a few high-signal facilities to inspect variation, seasonality, and missing months (cloud/QA).

[ ]:
```
if not ts.empty:
    top_ids = ts.groupby('plant_id')['no2_mean'].mean().
 ↪sort_values(ascending=False).head(3).index
    for pid in top_ids:
        sub = tsj[tsj['plant_id']==pid].sort_values('ym')
        plt.figure(figsize=(6,4))
        plt.plot(sub['ym'], sub['no2_mean'], marker='o')
        plt.title(f"TROPOMI NO  near {sub['name'].iloc[0]} (10 km buffer)")
        plt.xlabel('Month'); plt.ylabel('NO  column (mol/m²)'); plt.show()
else:
    print('NO  time series empty (EE auth/quota?). Re-run the EE cell.')
```