Nuclear operations with a high penetration of renewables: the case of France

Nicolas Astier (PSE & ENPC) and Frank A. Wolak (Stanford University)

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-
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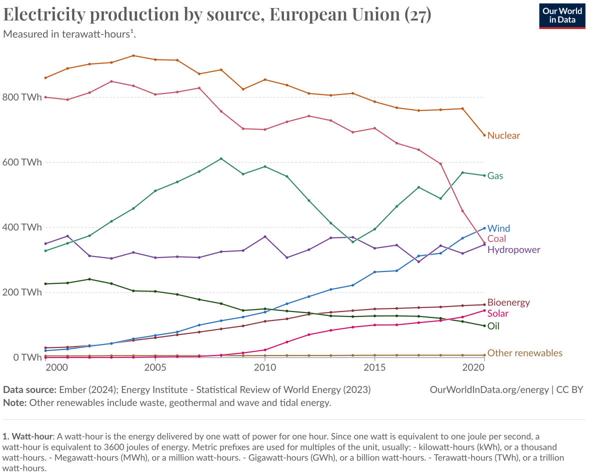
Nuclear and renewables as substitutes in the long-run



Generation mix

Nuclear and renewables: a (short-run) truce?

(source: https://medium.com/@Wbgeist/nuclear-energy-a-path-to-sustainable-progress-1ca05b8790c9)

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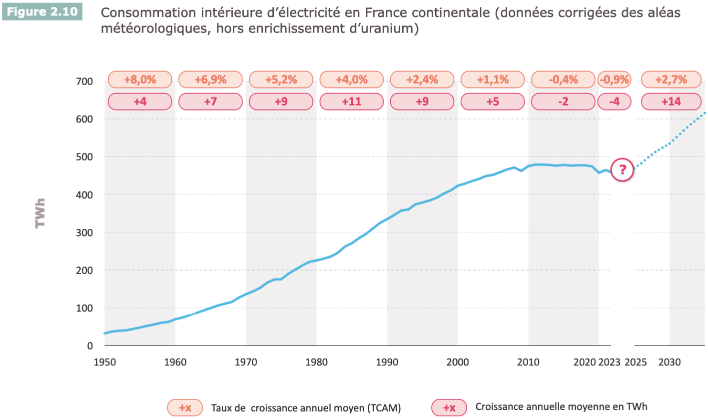
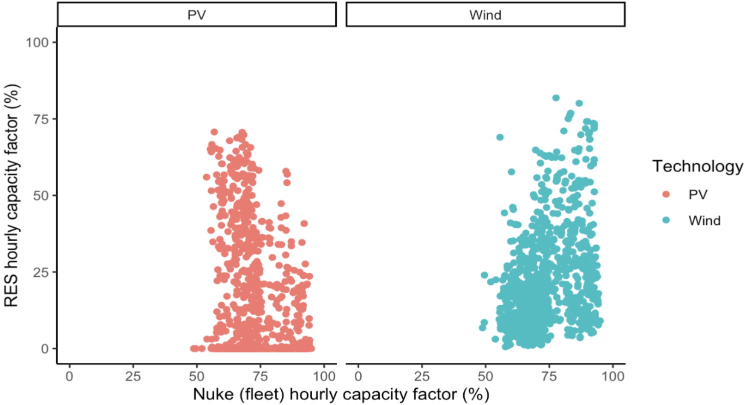


(source: Bilan prévisionnel 2023, RTE)

But wait a minute...?!



Sample of 1,000 randomly selected 15-min intervals in 2018 in France (data source: RTE)

This paper

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- **Preliminary results:**
  1. an increased exposure to solar generation (mostly distributed in France) is associated with more frequently binding minimum output constraints.
  2. despite flexible operations, the "supply response" to very low DA prices is far from perfect.

Outline

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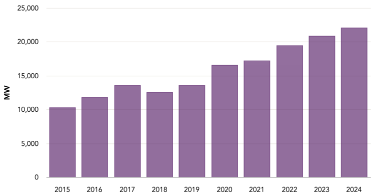
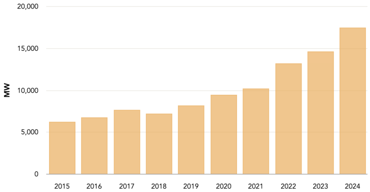
Wind and solar PV growth

Cumulative on-shore wind capacity:



Cumulative solar PV capacity:

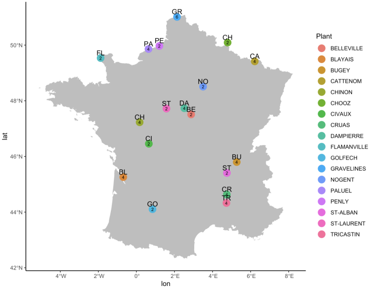


Total capacity of units of 1 MW or more, most of which connects (in France) to the distribution grid (source: RTE)

Remark: as of 2023, total solar PV capacity including installations < 1 MW was about 19 GW.

French nuclear fleet

- Commissioned between 1979 and 2002.
- Unit sizes: 900 MW (32 units), 1300 MW (20 units) or 1500 MW (4 units).



As of today, 18 facilities composed of a total of 56 units for an aggregate installed capacity of about 61 GW. Example

Remark: the two units of Fessenheim were shut down in Feb 2020 and are dropped from the analysis.

Operating constraints on nuclear units

Nuclear units typically face:

- a minimum output constraint (either nominal or driven by other factors), in a context where shutting them down is very costly.
- ramping constraints, limiting their ability to follow load variations.

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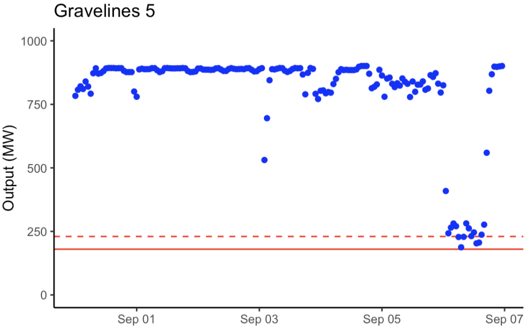

Hourly output over one week.

France and “flexible” nuclear operations

“Une question m’est régulièrement posée concernant la capacité de modulation des tranches du parc nucléaire français [...] En une trentaine de minutes, jusqu’à 90% d’avancement dans le cycle de production, il est possible d’ajuster à la hausse ou à la baisse 80% de la puissance d’un réacteur nucléaire.”

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⇒ In what follows, we focus on the minimum output constraint.

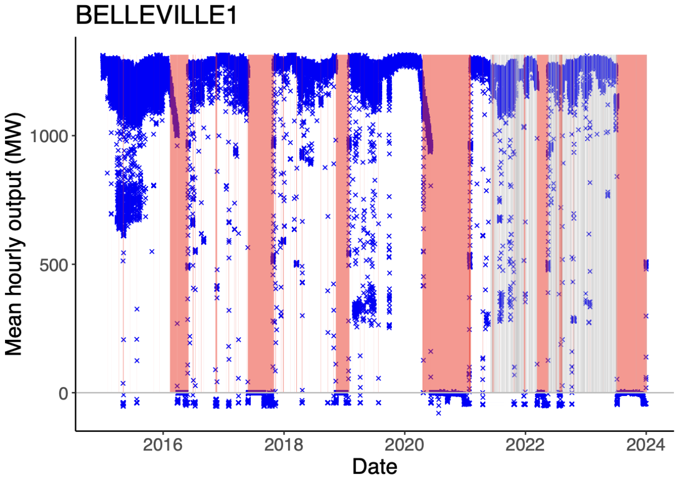
Outline

Data Sources

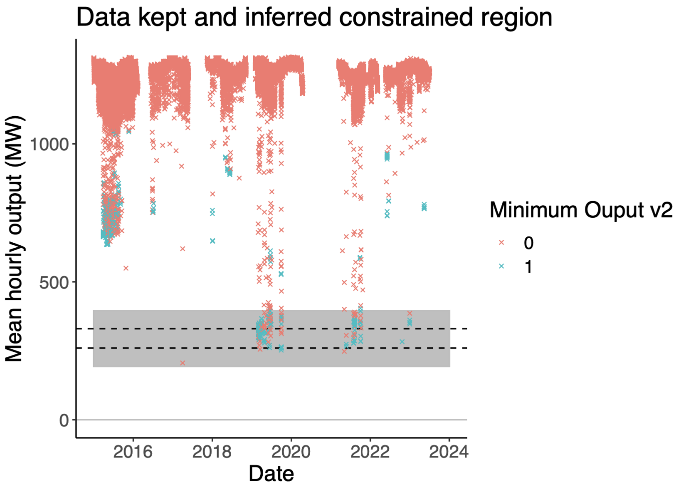
We use several public sources of data:

1. The inventory of French power plants provides the location (municipality), commissioning date, technology and installed capacity of the universe of power plants in France.
2. Unit-level hourly output for nuclear units between 1 January 2015 and 31 December 2023 (source: RTE). CF France CF USA
3. Unit-level outages for 2015-2023: start and end dates, type, description (source: RTE and EDF & scrapped data from ASN). Frequency
4. Nuke unit characteristics: nominal capacity, nominal minimum output level, maximum capacity available for secondary reserve, fuel type (source: EDF).
5. Hourly day-ahead prices (source: ENTSO-E).

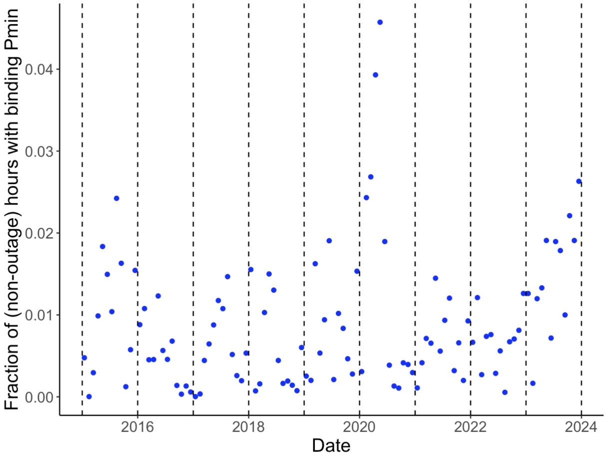
Unit-level output



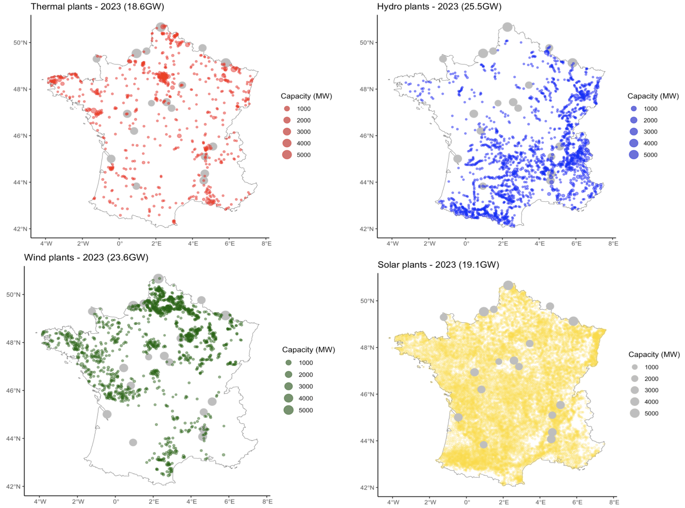
Minimum output constraint - Unit-level



Minimum output constraint - Frequency

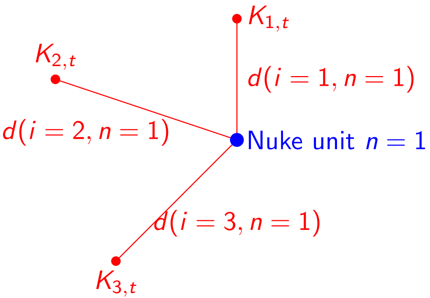


Location of nuke vs other facilities



Outline

Exposure of a nuke unit to another technology



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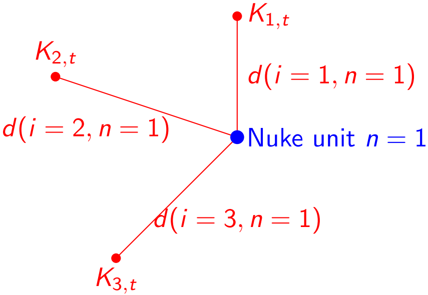

We define the "exposure" $X_{n,t,\tau}$ of nuclear unit n to technology τ at date t as:

$$X_{n,t,\tau} \equiv \sum_{i \in \text{Techno-}\tau \text{ at } t} \left(\frac{\max(d(i,n), d_0)}{d_0} \right)^{-\gamma} K_i$$

where $\gamma = 0.5$ and $d_0 = 1$km are tuning parameters.

Exposure of a nuke unit to another technology

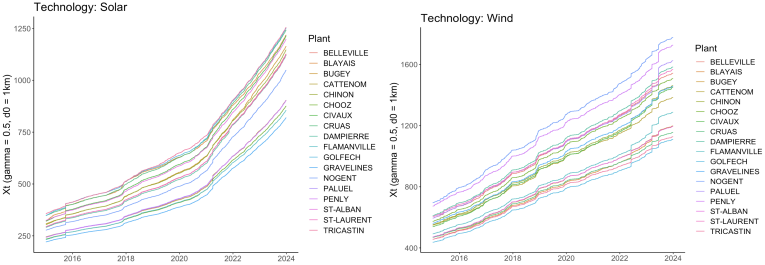

Figure: Obtained exposure metric (in MW) to solar (left panel) and wind (right panel) for the 18 nuclear facilities between 1 January 2015 and 31 December 2023 ($d_0 = 1$ km and $\gamma = 0.5$).

Approach

- Outcome variable: $Y_{h,n} \equiv$ dummy variable taking the value 1 if the minimum output constraint is assessed to be binding in hour h for unit n.

- Main explanatory variables: $X_{\tau,h,n} \equiv$ exposure metric of unit n in hour h to technology τ, with $\tau \in \{\text{wind, solar, hydro, thermal}\}$.

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- Models:

$$Y_{h,n} = \sum_{\tau} \beta_{\tau} X_{\tau,h,n} + \mu_n + \delta_y + \delta_m + \delta_d + \delta_h + \epsilon_{h,n}$$

where the error term is assumed either i.i.d. normal (linear probability model) or i.i.d. Gumbel (logit).

Outline

Regression results

	Dependent variable: Is minimum constraint binding? (Definition 1)							
	Linear probability model				*Logit*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X_PV	0.003 (0.006)	0.01 (0.010)	0.01 (0.011)	0.04 (0.022)	0.3 (0.691) [0.003]	0.8 (1.148) [0.007]	1.5 (1.091) [0.01]	6.0 (2.729) [0.05]
X_Wind	0.004 (0.005)	0.01 (0.009)	0.00 (0.010)	0.01 (0.023)	0.5 (0.545) [0.004]	0.8 (0.957) [0.007]	-0.4 (1.075) [-0.004]	2.0 (2.327) [0.02]
X_Hydro				0.04 (0.075)				9 (9.547) [0.08]
X_Therm				-0.02 (0.016)				-4 (2.565) [-0.03]
Unit FE	N	N	Y	Y	N	N	Y	Y
Year FE	N	Y	N	Y	N	Y	N	Y
Month of year FE	N	Y	N	Y	N	Y	N	Y
Day of week FE	N	Y	N	Y	N	Y	N	Y
Hour of day FE	N	Y	N	Y	N	Y	N	Y
Observations	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091
R^2	0.0003	0.013	0.006	0.019				
Log Likelihood					−134,063	−119,213	−126,495	−111,141

Note: Robust standard errors clustered at the unit level

Hourly effects LPM | Alternative definition | $\gamma = 0.25$ | $\gamma = 0.75$

Remark: $X_{\mathcal{T}}$ have been scaled (/1000) and range from 0.22 to 1.26 for PV and from 0.44 to 1.78 from wind.

Opportunity cost of inflexibility?

"Une question m'est régulièrement posée concernant la capacité de modulation des tranches du parc nucléaire français [...] En une trentaine de minutes, jusqu'à 90% d'avancement dans le cycle de production, il est possible d'ajuster à la hausse ou à la baisse 80% de la puissance d'un réacteur nucléaire."

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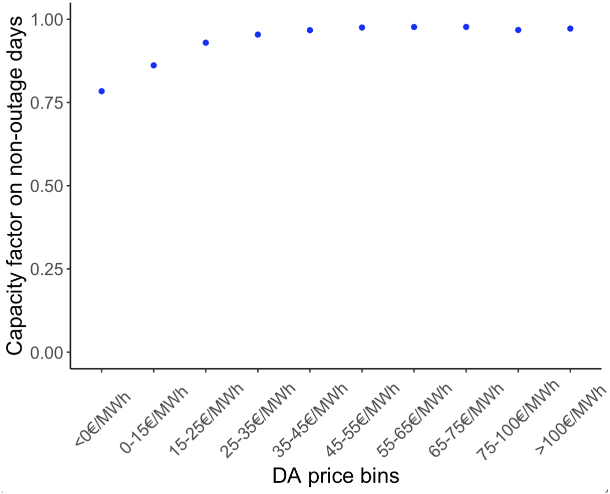

Opportunity cost of inflexibility?

1. We try to retrieve unit-level fuel cycles from outage data and keep the most credible ones ($\pm$20% of the unit-level median aggregate output during an imputed cycle).
2. We compute capacity factors conditional on being during the 90% first hours and the 10% last hours of the fuel cycle.

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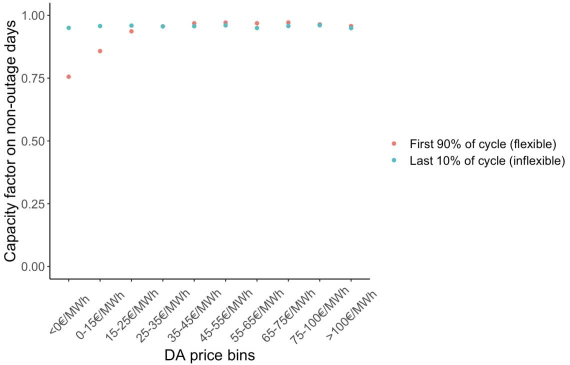

Outline

Next steps (non-exhaustive)

1. Back of the envelope monetary costs:
   - Minimum output constraint:

$$\underbrace{0.04}_{\uparrow \text{ freq}} \times \underbrace{5€/\text{MWh}}_{\mathbb{E}_h[(MC-p_h)^+]} \times \underbrace{200\text{MW}}_{P_{min}} \times \underbrace{8760}_{\#h/yr} = 350 \text{ k€/unit-yr}$$

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4. Expand the period of analysis: add year 2024 and (possibly) years prior to 2015.

Thank you!

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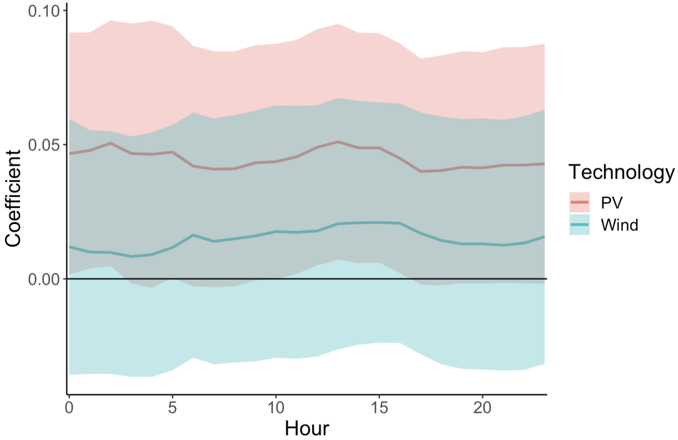
Hourly interactions (LPM)



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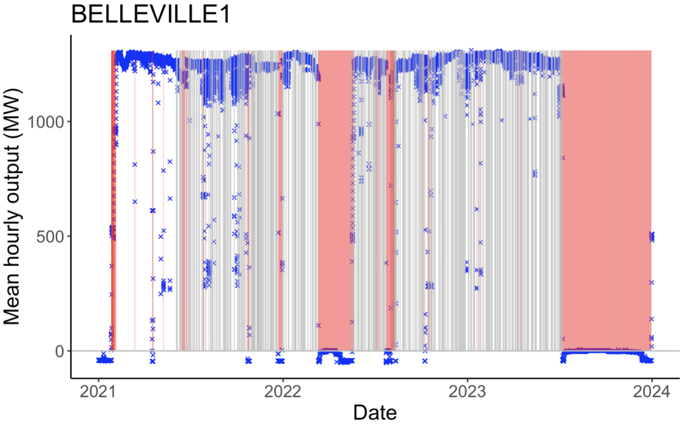
Dynamic minimum output constraint



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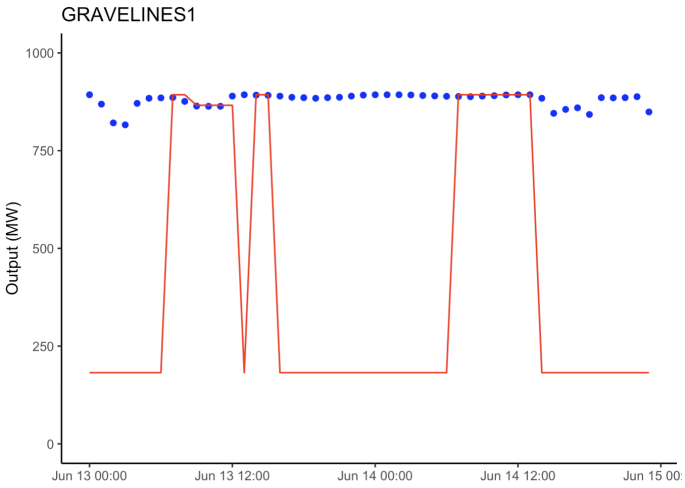

Back

$\gamma = 0.25$

	Dependent variable: Is minimum constraint binding? (Definition 1)							
	Linear probability model				*Logit*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X_PV	0.001	0.004	0.003	0.020	0.07	0.4	0.3	3
	(0.003)	(0.005)	(0.003)	(0.008)	(0.273)	(0.525)	(0.358)	(0.892)
X_Wind	0.001	0.003	-0.001	0.01	0.1	0.3	-0.1	1
	(0.002)	(0.004)	(0.003)	(0.009)	(0.236)	(0.425)	(0.352)	(0.908)
X_Hydro				0.05				7.5
				(0.022)				(2.827)
X_Therm				-0.008				-1.7
				(0.004)				(0.632)
Unit FE	N	N	Y	Y	N	N	Y	Y
Year FE	N	Y	N	Y	N	Y	N	Y
Month of year FE	N	Y	N	Y	N	Y	N	Y
Day of week FE	N	Y	N	Y	N	Y	N	Y
Hour of day FE	N	Y	N	Y	N	Y	N	Y
Observations	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091
R^2	0.0003	0.013	0.006	0.019				
Log Likelihood					−134,091	−119,216	−126,541	−110,796
Note:					Robust standard errors clustered at the unit level			

Back

$\gamma = 0.75$

	Dependent variable: Is minimum constraint binding? (Definition 1)							
	Linear probability model				*Logit*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X_PV	0.01	0.03	0.04	0.1	1.3	2.8	5.2	13
	(0.017)	(0.028)	(0.032)	(0.060)	(1.887)	(3.138)	(3.043)	(7.710)
X_Wind	0.0177	0.027	-0.010	0.005	2	3	-1	1
	(0.014)	(0.028)	(0.031)	(0.065)	(1.424)	(2.718)	(3.068)	(6.286)
X_Hydro				-0.1				0
				(0.231)				(27.932)
X_Therm				-0.04				0
				(0.063)				(27.932)
Unit FE	N	N	Y	Y	N	N	Y	Y
Year FE	N	Y	N	Y	N	Y	N	Y
Month of year FE	N	Y	N	Y	N	Y	N	Y
Day of week FE	N	Y	N	Y	N	Y	N	Y
Hour of day FE	N	Y	N	Y	N	Y	N	Y
Observations	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091
R^2	0.0004	0.013	0.006	0.019				
Log Likelihood					−133,981	−119,123	−126,478	−111,356
Note:					Robust standard errors clustered at the unit level			

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Alternative definition of the minimum output constraint

Minimum output constraint binds in a given hour of a non-outage day if:

1. output is between 10% and 80% of nominal capacity.
2. the absolute change in output in hour $h-1$ vs h is lower than 20 MW.

	Dependent variable: Is minimum constraint binding? (Definition 2 - $\gamma = 0.5$)							
	Linear probability model				*Logit*			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X_PV	0.001	0.00	0.01	0.04	0.1	0	0.5	3.7
	(0.007)	(0.009)	(0.014)	(0.022)	(0.556)	(1.273)	(1.233)	(2.158)
X_Wind	0.007	0.00	0.01	0.01	0.6	0.3	0.4	1
	(0.005)	(0.009)	(0.014)	(0.022)	(0.414)	(0.735)	(1.205)	(1.909)
X_Hydro				0.0				0
				(0.080)				(8.167)
X_Therm				0.01				0
				(0.019)				(2.385)
Unit FE	N	N	Y	Y	N	N	Y	Y
Year FE	N	Y	N	Y	N	Y	N	Y
Month of year FE	N	Y	N	Y	N	Y	N	Y
Day of week FE	N	Y	N	Y	N	Y	N	Y
Hour of day FE	N	Y	N	Y	N	Y	N	Y
Observations	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091	2,736,091
R^2	0.0004	0.016	0.006	0.022				
Log Likelihood					−171,658	−153,365	−164,562	−146,055
Note:					Robust standard errors clustered at the unit level			

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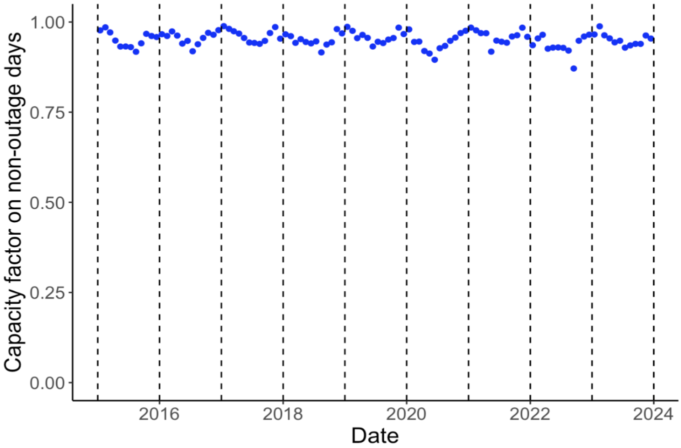
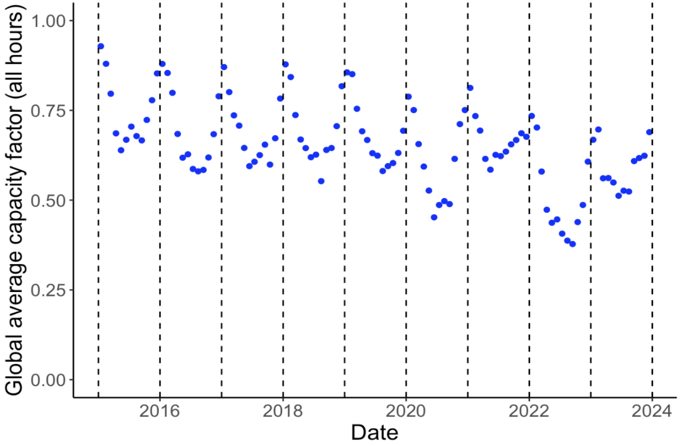
Capacity factor conditional on being on a non-outage day



Unconditional capacity factor



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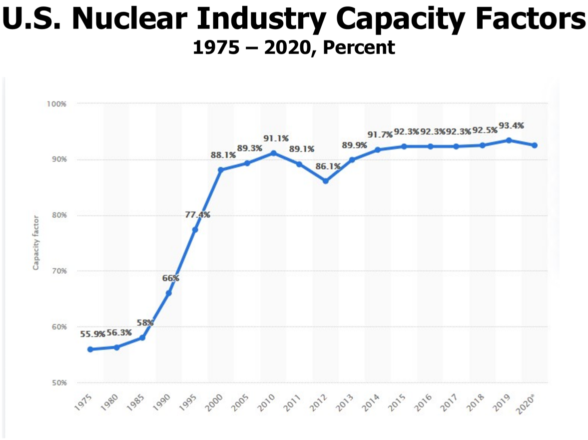
Unconditional capacity factor



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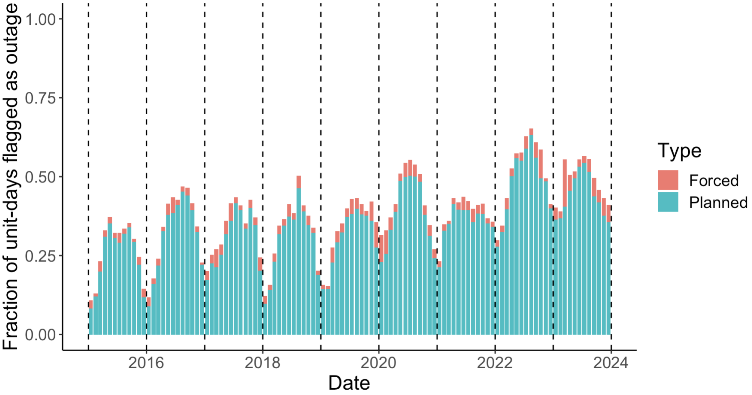
Frequency of outages



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Example of 2-unit nuke facility (Golfech)

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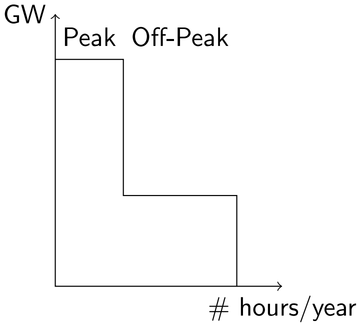
Nuclear and renewables as substitutes in the long-run



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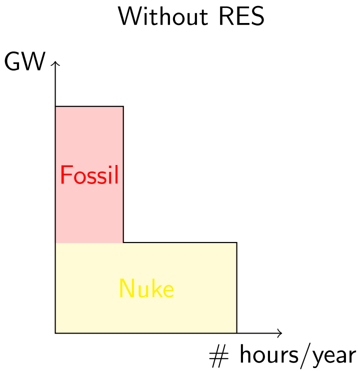

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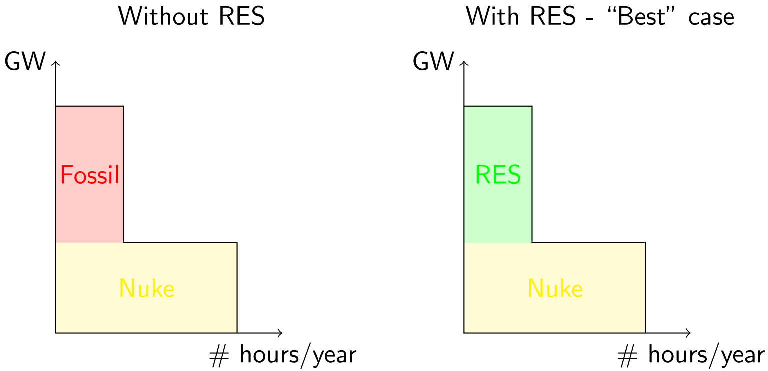

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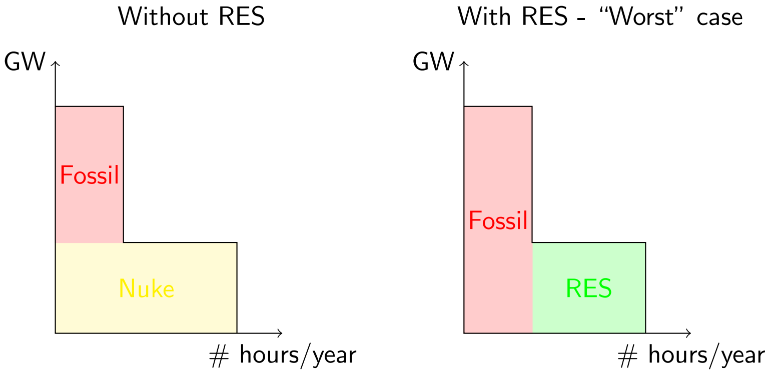

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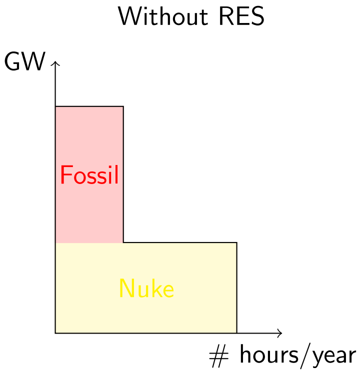

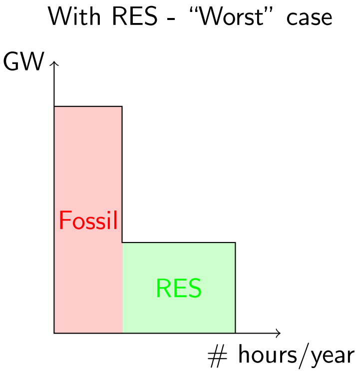

⇒ See for example Green and Léautier (2015).

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