Nuclear Operations with a High Penetration of Intermittent Renewables: The Case of France

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Can Nuclear and Wind & Solar Jointly Provide Reliable Low-Carbon Electricity?

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

A Nuclear Renaissance in the United States?

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Atomic energy has attracted influencers, spawned merch and even made a cameo on ESPN's 'College GameDay'

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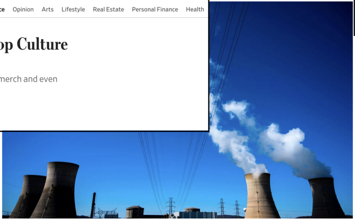
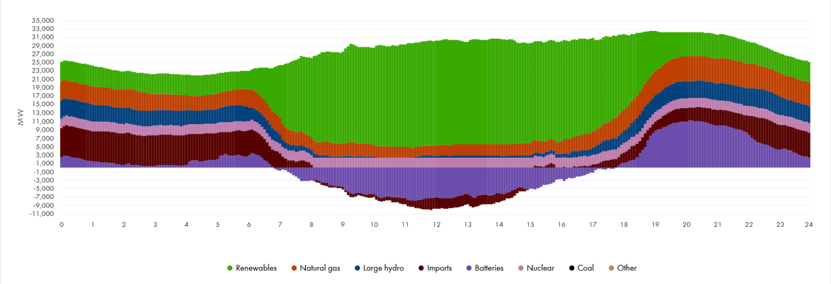


Apparent lack of "flexibility" of nuclear units–CAISO

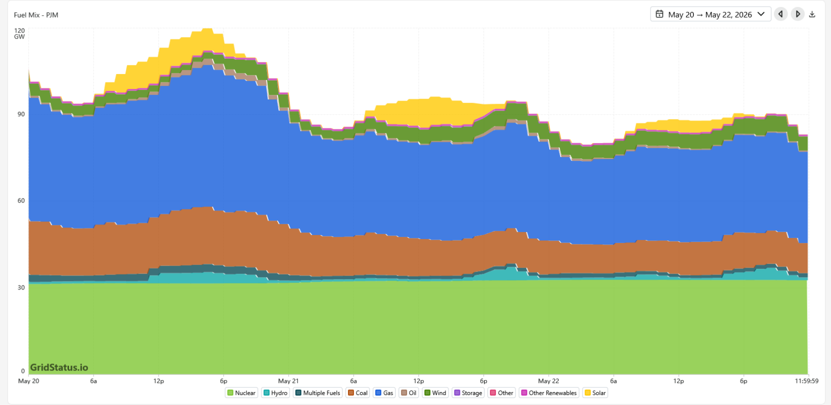
Nuclear units are very large (typical size $\equiv$ 1 GW), costly and complicated (operating constraints, fuel management, safety, etc.) machines.



California ISO n 20 May 2026 (source: www.caiso.com/todays-outlook)

Diablo Canyon nuclear plant is operating at close to full capacity (2,280 MW) all hours of the day

Apparent lack of "flexibility" of nuclear units–PJM

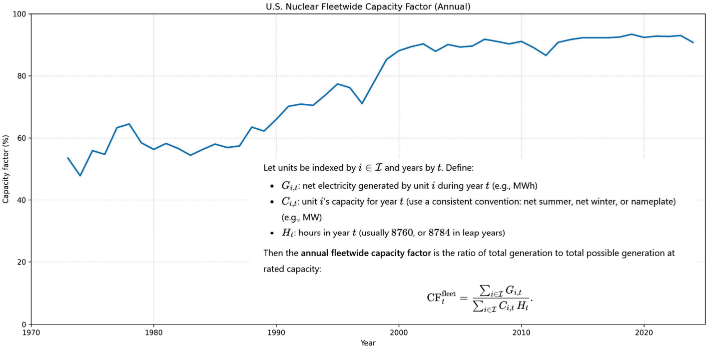


PJM from 20 May 2026 to 22 May 2026 (source: www.gridstatus.io/)

PJM nuclear plants are operating at close to full capacity (32 GW) all hours of this multi-day time period.

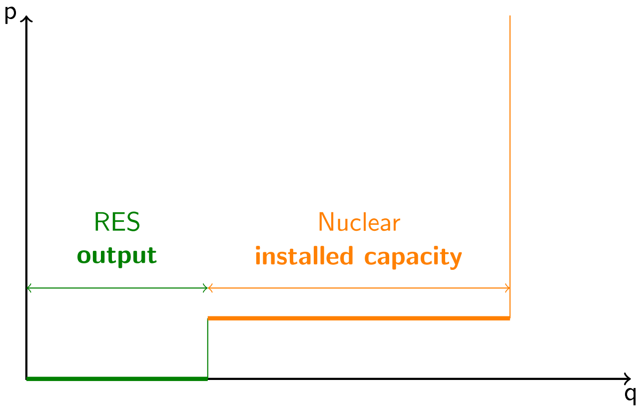
Economic Benefit of "Inflexible" Operation in US

US Annual Fleetwide Capacity Factor 1973 to 2025

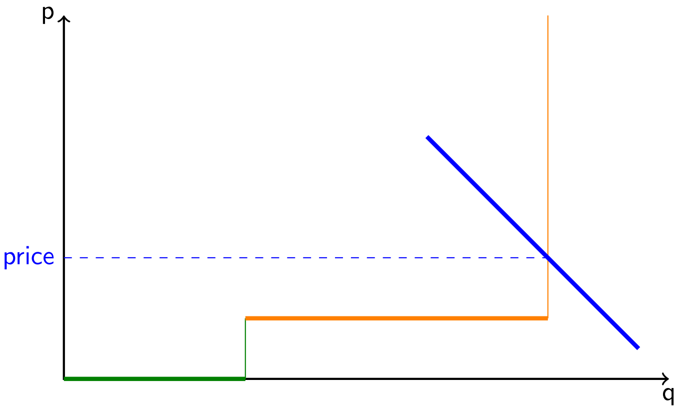


Annual Fleetwide Capacity Factor of French Nuclear Units is between 70% to 77%, compared to 92% to 93% in the US

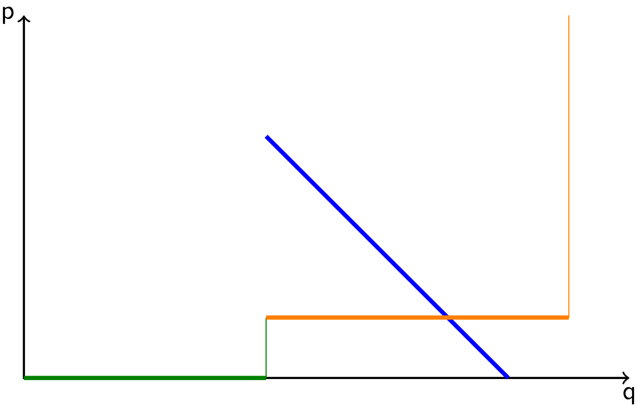
Stylized Model of the Economics of Nuclear Flexibility



Stylized Model of the Economics of Nuclear Flexibility



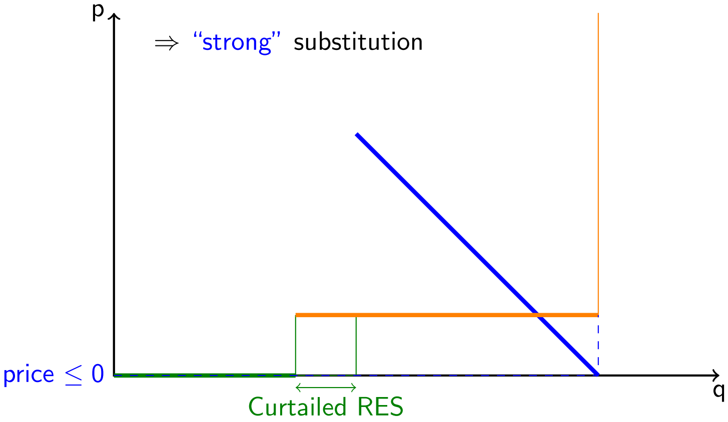
Stylized Model of the Economics of Nuclear Flexibility



Stylized Model of the Economics of Nuclear Flexibility

Case 1: inflexible nuclear

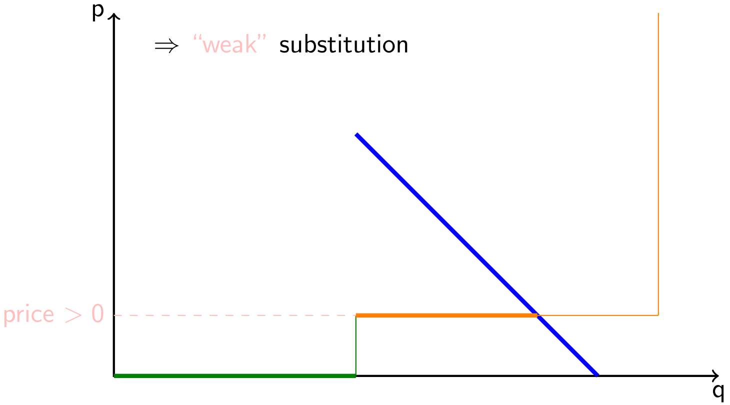
⇒ "strong" substitution



Stylized Model of the Economics of Nuclear Flexibility

Case 2: flexible nuclear

⇒ “weak” substitution



France obtains vast majority of electricity from nuclear power

- France hosts a nuclear fleet of 60+GW: 18 facilities composed of a total of 57 units (as of 31 December 2024).
- The installed capacity of intermittent renewables has reached:
  - $\sim$ 24 GW of wind.
  - $\sim$ 24 GW of solar.

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France 'flexes' nuclear output as solar reshapes European energy

Country's reactors are adjusting output more frequently as more renewables come online

$\Rightarrow$ Nuclear 70% + renewables can now (theoretically) cover domestic demand during all hours, hydro 14%, wind 8% and solar 4%.

Preview of results

1. Nuclear operations in France are flexible and can thus respond to renewable output.

   ⇒ A "weak substitution" regime is possible.

2. Associated opportunity costs seem relatively limited at the present time in France:
   - Loss of capacity factor: a few percentage point from direct effect. Indirect effect through maintenance and outages may be larger.
   - Environmental externalities: not detected from monthly plant-level data.
   - Safety: Additional load-following event predicts small increase in unit's hazard rate of an emergency shut down.

3. However, downward flexibility faces increasingly binding operating constraints: in 2024, hours during which available downward nuclear flexibility was exhausted are strongly associated with zero or negative prices.

   ⇒ Emergence of a "strong substitution" regime during hours of low demand and high renewable production.

Outline

Outline

Relevant Literature

- (Short-run) substituability of nukes and renewables:
  - Industry reports have discussed flexible operations of nuclear units, for example in France (Morilhat et al., 2019; EDF, 2026) and Germany (Grünwald and Caviezel, 2017).
  - Le Coq and Schwenen (WIP) study the association between renewables and forced outages/load-following events in the U.S.
- Role of nuclear to decarbonize electricity supply: "negative learning-by-doing" (Grubler, 2010; Boccard, 2014; Rangel and Lévêque, 2015), a short-lived "renaissance" (Davis, 2012; Joskow and Parsons, 2012), social costs of early phase outs (Bauer et al., 2017; Severnini, 2017; Adler et al. 2020; Jarvis et al., 2022), recent renewed interest (Andersson and Finnegan, 2024; Makarin et al., 2024).
- Nuclear operations (efficiency, safety, strategy behaviors): Davis and Wolfram (2012), Hausman (2014), Davis and Hausman (2016), Liski and Vehviläinen (2018), Lundin (2021).

Nuclear energy in France

- France hosts a nuclear fleet of 60+GW. In comparison:
  - Annual peak (domestic) demand is in the range 80-100 GW.
  - Mean hourly (domestic) demand is about 50 GWh (plus 5 to 10 GWh of exports).

  ⇒ Given the (very) large installed nuclear capacity relative to demand, nuclear units have been performing "load following" for several decades (i.e., before the renewables era).

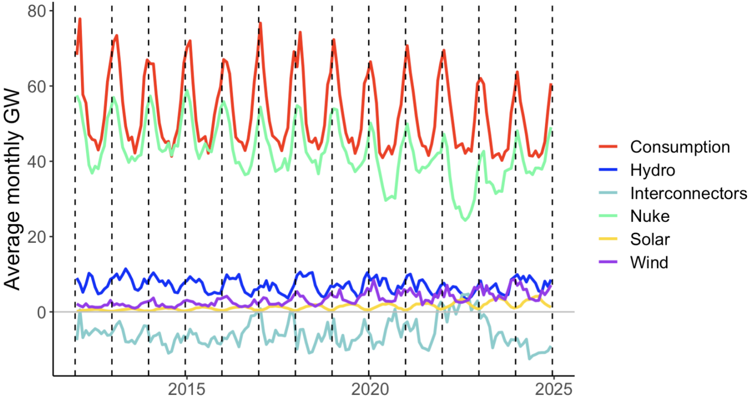
- All units are owned and operated by the same firm. Associated incentives to exert market power may be somewhat mitigated through:
  - vertical integration (EDF remains the dominant retailer).
  - a partial financial divesture mechanism (ARENH) between July 2011 and December 2025.
  - regulatory oversight of bids in market auctions.

  ⇒ Exploration of strategic incentives is left for further research.

Data Sources

1. Unit-level:
    - hourly output of nuclear units for 2012-2024 (RTE and Entso-e).
    - outages for 2015-2024: start and end dates, type (forced/planned), minimal description (RTE, EDF and ASNR).
    - dates of automatic shut downs and manual emergency interventions for 2015-2024 (ASNR).
    - nominal capacity, nominal minimum output level, maximum capacity commited to reserves (EDF).
    - minimum output when higher than nominal ($>$ 100MW) for June 2021-2024 (EDF).
2. (Half-)hourly main country-level outcomes: gross consumption, generation by technology, imports/exports for 2012-2024 (RTE and Entso-e).
3. The inventory of French power plants provides the location (municipality), commissioning date, technology and installed capacity of the universe of power plants in France (Data.gouv).
4. Hourly day-ahead prices (Entso-e).
5. Yearly environmental reports by plants for 2019-2024 (EDF).

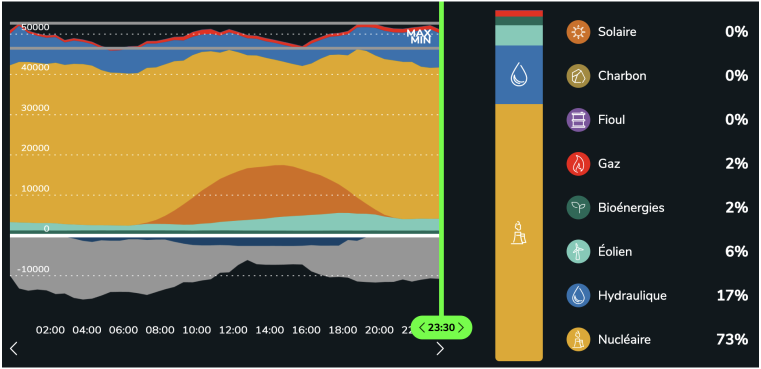
Monthly electricity consumption and output



Remark: Wind and solar output includes TSO's estimate of distributed generation.

Outline

Nuke operations in France (15 August 2025)

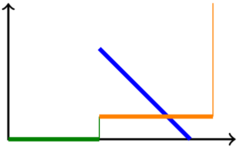


(source: www.rte-france.com/eco2mix)

Aggregate substitution between nuke and RES

Question: At the aggregate *country-level*, by how much does the nuclear fleet adjust (on average) output in response to varying residual demand/renewable production?

1. Dependent variable $Y_h \equiv$ nuclear output (GWh) in hour h.
2. Explanatory variable $RES_h \equiv$ joint output (GWh) from wind and solar in hour h.
3. Residual demand $RD_h \equiv$ gross demand plus net exports minus net hydro minus must-take biothermal (GWh).



Specifications:

- $Y_h = \alpha + \beta RES_h + \gamma RD_h + \sum_T \delta_{h \in T} + \epsilon_h$
- $Y_h = \sum_{b \in \{\text{bins RD-RES}\}} (\alpha_b + \beta_b RES_h + \gamma_b RD_h) + \sum_T \delta_{h \in T} + \epsilon_h$

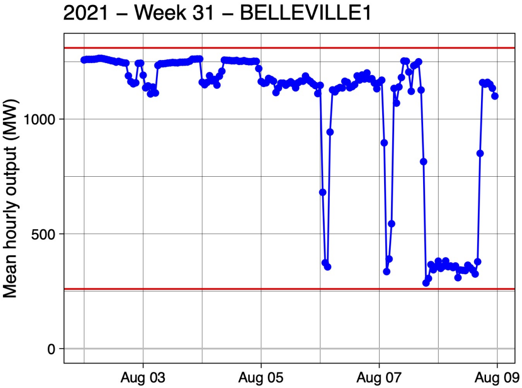
Aggregate substitution between nuke and RES

Dependent variable: hourly total nuclear generation (2012-2024)

	(1)	(2)	(3)	(4)
RES_h (GWh)	-0.78 (0.0064)	-0.66 (0.0075)		
RD_h (GWh)	0.77 (0.0036)	0.63 (0.0067)		
RES_h:bin$<$25GW			-0.3 (0.26)	-0.8 (0.15)
RD_h:bin$<$25GW			0.4 (0.25)	0.7 (0.15)
RES_h:bin25-40GW			-1.04 (0.011)	-0.85 (0.0098)
RD_h:bin25-40GW			1.09 (0.011)	0.85 (0.0095)
RES_h:bin40-63GW			-0.70 (0.0095)	-0.56 (0.0085)
RD_h:bin40-63GW			0.71 (0.0054)	0.56 (0.008)
RES_h:bin$>$63GW			-0.43 (0.048)	-0.24 (0.014)
RES_h:bin$>$63GW			0.44 (0.028)	0.25 (0.0091)
Day-of-sample FE	N	Y	N	Y
Observations	113,973	113,973	113,973	113,973
R2	0.919	0.994	0.930	0.995

Quantifying load following

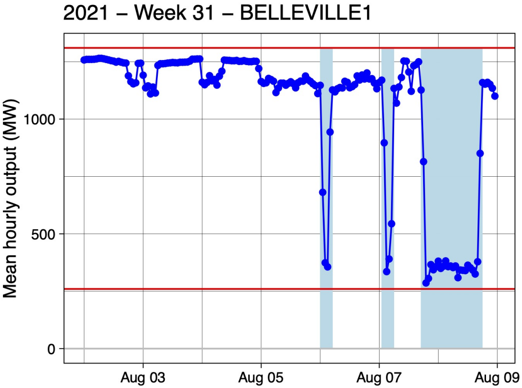
Illustrative example of the hourly output of a single unit over one week in 2021. Red line is nominal minimum output constraint (20% of unit's nominal capacity)



Quantifying load following

We define "load following events" as instances where the unit:

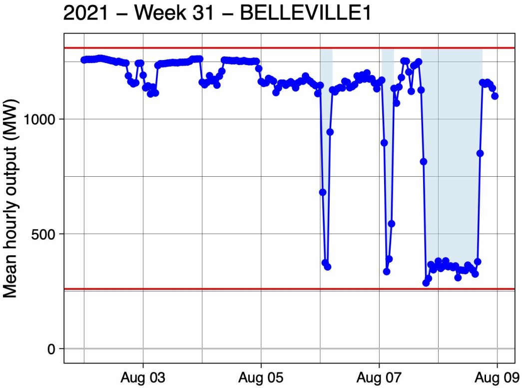
1. is not outaged.
2. produces below 75% of its installed capacity.



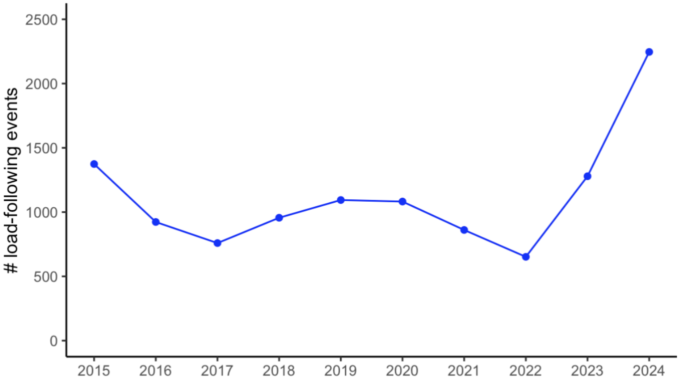
Quantifying load following

In the next part, we use "lost energy" (right panel) to measure the intensity of load following.

Remark: using the sum of the absolute value of first differences in hourly output (as in Blanchard and Massol (2025)) yields similar results.



Load following events over time



Number of detected load-following events per year (2015-2024).

Outline

Indirect loss of capacity factor

Load following may also have indirect impacts on capacity factors through:

1. Decreased fuel efficiency (overall electricity output per input ton of uranium).
2. Longer subsequent refueling outages due to increased maintenance.
3. More frequent forced outages.

Indirect loss of capacity factor

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lost energy per GW	0.0028		-0.01		0.2		
	(0.00050)		(0.0067)		(0.081)		
Log(Lost energy)		0.025		0.03		0.23	
		(0.0042)		(0.023)		(0.045)	
Decenal visit (Y/N)			24	1.1			
			(2.8)	(0.065)			
Fitted lost energy per GW							0.7
							0.25)
unit FE	Y	Y	Y	Y	Y	Y	Y
Observations	367	367	360	360	344	344	344
R2	0.682	0.673	0.507	0.443	0.269	0.297	0.201

Outcomes:

(1)-(2) Fuel-cycle output (TWh) by installed GW (level - log).

(3)-(4) Duration of subsequent refueling outage in weeks (level - log).

(5)-(7) Number of forced outage hours, removing outliers (level - log - level instrumented with residual demand).

Safety

- Measuring safety in the context of nuclear operations is challenging due to asymmetric information (Bizet, Bonev and Lévêque (2022)).
- The existing literature usually proxies “safety” with emergency automatic shut downs of reactors (e.g. Hausman (2014)), which are arguably hard to conceal.
- We take a similar approach and use data from the nuclear safety agency to restrict attention to:
  - Automated shut downs
  - Manuel emergency interventions

Cox proportional hazards model

- $t \equiv$ time since the beginning of a fuel cycle (full-load hours).
- $T \equiv$ date at which the first emergency event occurs for a given unit, treated as a random variable with cdf $F(.)$ and pdf $f(.)$.

- The hazard function $h(.)$ is the instantaneous probability of failure conditional on being still alive at time t:

$$h(t) \equiv \frac{f(t)}{1 - F(t)}$$

- The Cox proportional hazards model assumes that the hazard function $h_i(.)$ for unit i may be parametrized as:

$$h_i(t, \theta) \equiv \exp(\theta^T x_{it}) h_0(t)$$

- Key features:
  - $h_0(.)$ does not have to be specified.
  - θ is estimated using partial maximum likelihood. Detail

Partial Likelihood Estimation Results

	(1)	(2)	(3)	(4)
Full-load hours of lost energy	0.0018	0.0020		
	(0.00073)	(0.00078)		
# load following events			0.009	0.010
			(0.0033)	(0.0035)
vintage CP1		-0.3		-0.4
		(0.25)		(0.25)
vintage CP2		-0.5		-0.5
		(0.28)		(0.28)
vintage P4		0.0		0.0
		(0.287)		(0.288)
vintage P'4		-0.4		-0.4
		(0.28)		(0.28)
vintage N4		-0.6		-0.6
		(0.37)		(0.37)

$\Rightarrow$ Small marginal effect on the hazard rate for an emergency event of an additional load-following event during fuel cycle. Recall increasing number of load-following events during unit-level fuel cycles.

Annual Distribution of Unit-Level Load-Following Events

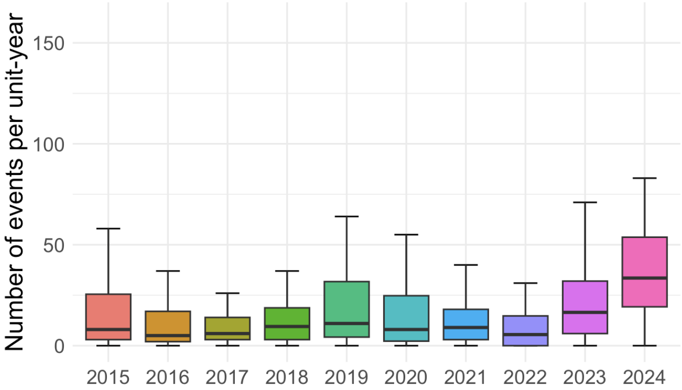


Figure: Distribution (boxplots) of the number of load-following events performed by each unit in a given year.

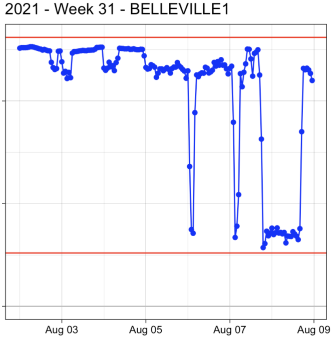
⇒ Substantial number (greater than 10) unit-level load-following events in a 12 to 18 month fuel cycle.

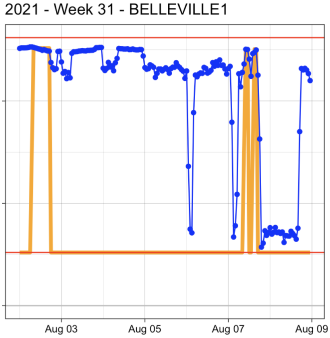
Outline

Limits to load following

Nuclear units typically face a minimum output constraint, which can be:

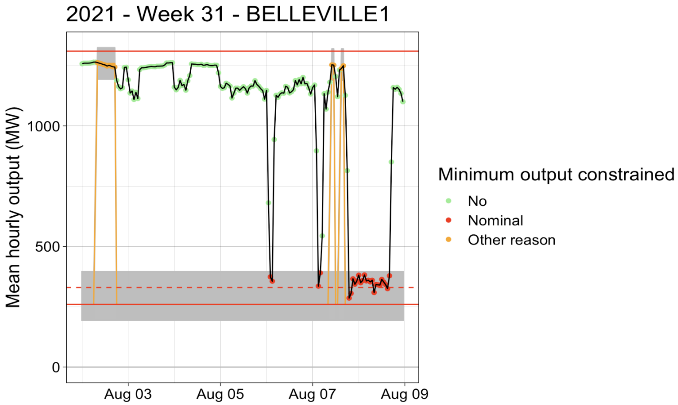
- either nominal (safe operations of the unit).
- or driven by other factors (e.g. grid stability).





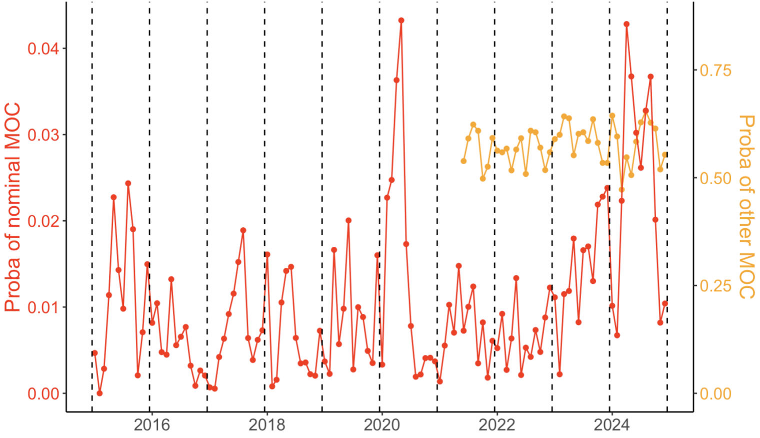
Nominal MOC Other example

Minimum output constraints - Definitions



We restrict attention to 2015-2024 (available outage data) to exclude false positives due to transient ramping up/down during outages.

Minimum output constraints - Conditional probability



Fraction of hours for nominal MOC (resp.MOC due to other factors) was binding during non-outaged hours.

Minimum output constraint - Timing

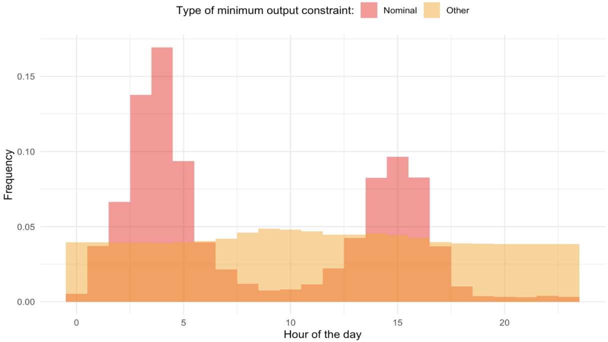


Figure: Histogram of the hours of the day when the minimum output constraints are inferred to bind.

Nominal MOC broken down by year
Other MOC broken down by year

Minimum output constraint - Fuel cycle

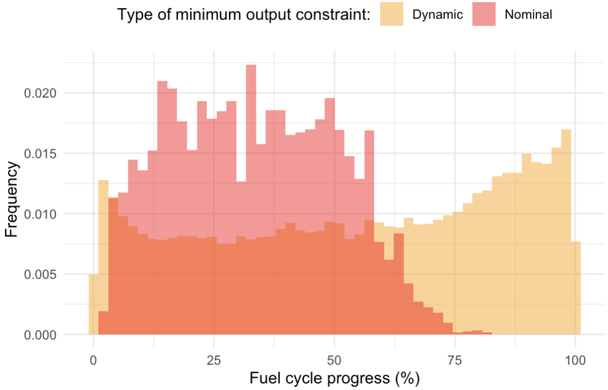


Figure: Occurrences of minimum output constraints (unit-hour observations) as a function of the position of the hour within the fuel cycle of the unit.

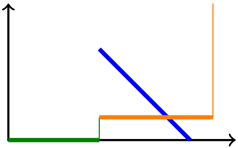
Example of fuel cycle

Empirical strategy (dataset ≡ fleet-level time series)

- Question: at the *country-level*, to which extent does increasing output from wind & solar cause minimum output constraints to bind more often?

- Main variables:

1. Dependent variable $Y_h \equiv$ number of units in hour h reaching their MOC (nominal, due to other factors, or either).
2. Explanatory variable $RES_h \equiv$ joint output from wind and solar (in GWh) in hour h.
3. Residual demand $RD_h \equiv$ gross hourly demand plus net exports minus net hydro minus must-take biothermal (in GWh).



- Specification:

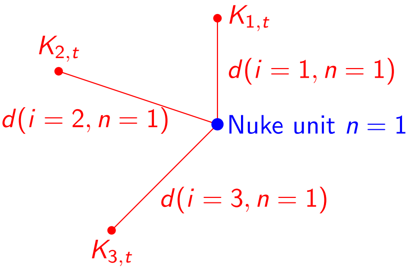
$$Y_h = \alpha + \beta RES_h + \gamma RD_h + \sum_T \delta_{h \in T} + \epsilon_h$$

Results

	Dependent variable: # of constrained units in hour *h*								
	Nominal (2015-2024)			Other (Jun 2021-2024)			Either (Jun 2021-2024)		
	(1)	(2)	(3)	(4)	(5)	(6)	(6)	(7)	(8)
RES_h (GWh)	0.080	0.306		-0.15	-0.06		-0.04	0.31	
	(0.0014)	(0.003)		(0.0065)	(0.0081)		(0.0068)	(0.01)	
RD_h (GWh)	-0.0263	-0.283	-0.287	0.440	0.41	0.39	0.401	0.05	0.03
	(0.00043)	(0.0027)	(0.0027)	(0.0033)	(0.0085)	(0.0083)	(0.0035)	(0.011)	(0.010)
$Solar_h$ (GWh)			0.320			0.01			0.38
			(0.0032)			(0.0081)			(0.0099)
$Wind_h$ (GWh)			0.267			-0.34			0.01
			(0.0031)			(0.011)			(0.0131)
Day-of-sample FE	N	Y	Y	N	Y	Y	N	Y	Y
Observation	87,672	87,672	87,672	31,441	31,441	31,441	31,441	31,441	31,441
R2	0.111	0.667	0.670	0.356	0.843	0.850	0.317	0.825	0.834

Table: Relationship between wind and solar output and the occurrence of minimum output constraints. Robust standard errors are clustered by day-of-sample.

Exposure of a nuke unit to another technology



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.

Maps as of 2024

Exposure of nuke locations to wind and solar

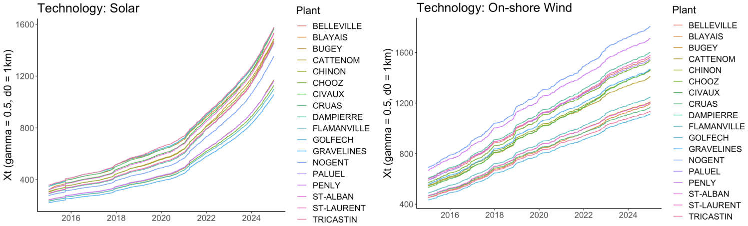


Figure: Obtained exposure metric (in MW) to solar (left panel) and wind (right panel) for the 18 nuclear facilities between 1 January 2015 and 31 December 2024 ($d_0 = 1$ km and $\gamma = 0.5$).

Empirical strategy (dataset $\equiv$ panel)

- 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 (unit-hour-level dataset).
- Main explanatory variables:
  - $X_{\tau,h,n} \equiv$ exposure metric of unit n in hour h to technology τ, with $\tau \in \{\text{wind, solar, hydro, thermal}\}$.
  - $W_{\tau,h,n} \equiv$ hourly output in hour h from technology τ allocated to the location of unit n:

$$W_{\tau,h,n} \equiv \frac{X_{\tau,h,n}}{\sum_m X_{\tau,h,m}} S_{\tau,h}$$

    where $S_{\tau,h} \equiv$ aggregate national output of technology τ in hour h.
- Specification: linear probability model

$$Y_{h,n} = \alpha + \beta_1 RES_h + \beta_2 W_{RES,h,n} + \gamma RD_h + \sum_T \delta_{h \in T} + \lambda_n + \epsilon_{h,n}$$

Results for nominal MOC

Dependent Variable:	Is nominal MOC binding? ($\gamma = 0.5$, sample = non-outage hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	0.0085	0.0083			
	(6.8e-05)	(0.00012)			
RD_h (GWh)	-0.00765	-0.00764	-0.00777	-0.00776	-0.0080
	(5.8e-05)	(5.8e-05)	(5.9e-05)	(5.9e-05)	(6.1e-05)
$W_{RES,h,n}$ (GWh)		0.008			
		(0.0035)			
$Solar_h$ (GWh)			0.0090	0.0085	0.0085
			(7.4e-05)	(0.00015)	(0.00015)
$Wind_h$ (GWh)			0.0074	0.0076	0.0076
			(7.1e-05)	(0.00017)	(0.00017)
$W_{solar,h,n}$ (GWh)				0.016	0.023
				(0.0045)	(0.0045)
$W_{wind,h,n}$ (GWh)				-0.011	-0.001
				(0.0055)	(0.00555)
$X_{hydro,h,n}$					-0.59
					(0.032)
$X_{therm,h,n}$					-0.9
					(0.083)
Num.Obs.	3,188,823	3,188,823	3,188,823	3,188,823	3,188,823
R2	0.070	0.070	0.071	0.071	0.071

$\gamma = 0.25$ | $\gamma = 0.75$ | Other MOC $\gamma = 0.25$ | Other MOC $\gamma = 0.5$ | Other MOC $\gamma = 0.75$

Sample = all hours (nominal) | Sample = all hours (other)

Remaining downward flexibility

- At any given point in time, a given unit must be either:
  - Outaged or down: refueling, planned/forced outages, hot shut downs.
  - At its minimum output level: nominal or dynamic.
  - Or still flexible.

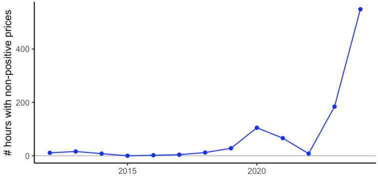
- We define the "remaining flexibility" of the fleet in hour h, RF_h, as:

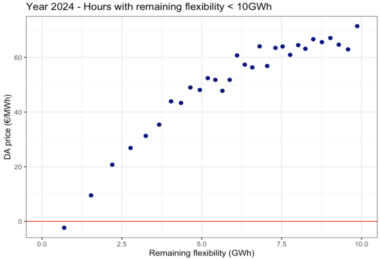
$$RF_h \equiv \sum_n (P_{n,h} - P_{min,n,h})\mathbf{1}[n \in \{\text{flexible in hour } h\}]$$

where $P_{n,h}$ is the observed output and $P_{min,n,h}$ the MOC.

Relationship with spot prices

In 2024 (and 2025), France experienced a spike in negative prices...





...which strongly correlates with a lack of remaining flexibility from the nuclear fleet.

$\Rightarrow$ Emergence of a "strong substitution" regime during many hours.

Wrapping-up

1. Nuclear operations in France are flexible and are responsive to renewable output variations.

   ⇒ An example for other jurisdictions that a "weak substitution" regime between nuclear and renewables is possible.

2. Associated opportunity costs (loss of capacity factor, environmental externalities) seem limited at the present time in France

   ⇒ Empirical evidence that additional load following event in a fuel cycle increases probability of automatic system shutdown

3. Downward flexibility of units faces increasingly binding operating constraints: in 2024, hours during which available downward nuclear flexibility was exhausted are strongly associated with zero or negative prices.

   ⇒ Emergence of a "strong substitution" regime during hours of low demand and high renewable production, even in France.

Thank you!

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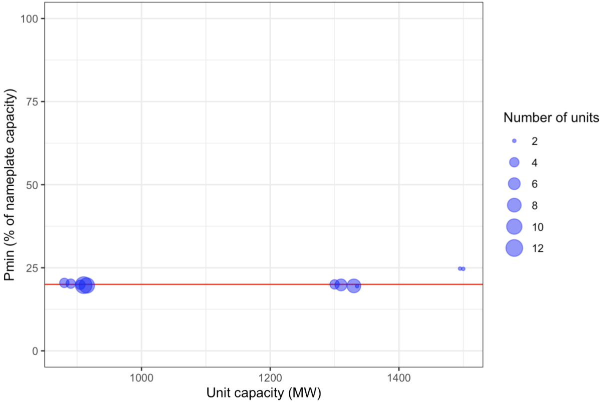
Nominal minimum output constraints



Units' minimum output level (in % of nominal capacity) as a function of nominal capacity.

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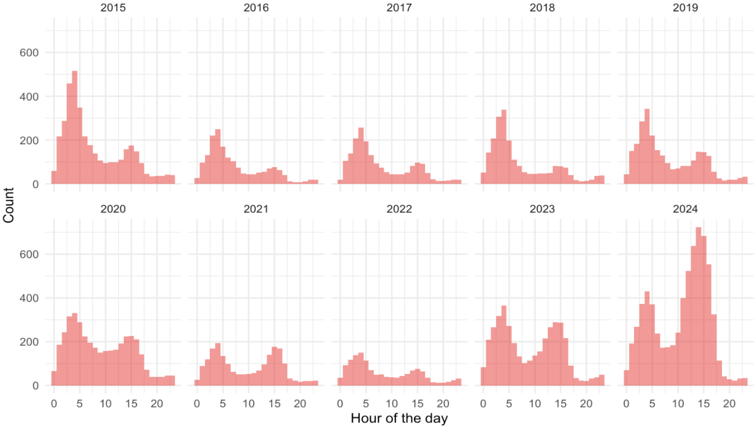
Hour of nominal MOC by year



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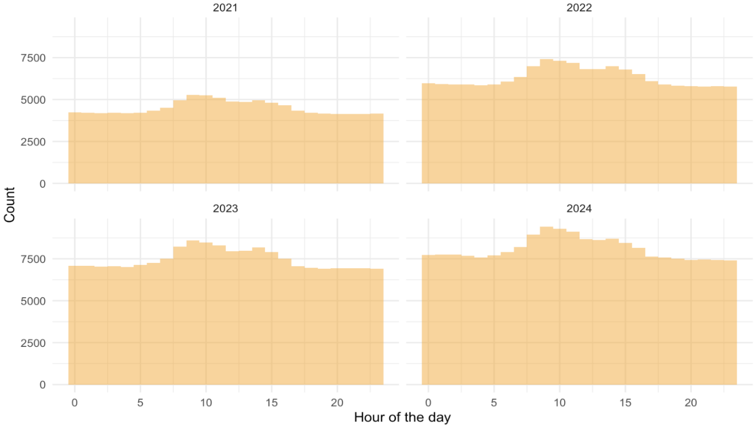
Hour of other MOC by year



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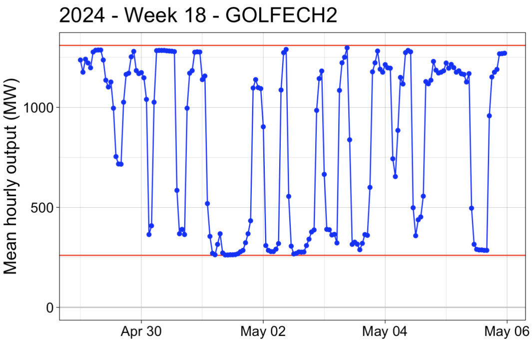
Other example of flexible operations



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Other MOC - $\gamma = 0.5$

Dependent Variable:	Is MOC binding for other reasons? ($\gamma = 0.5$, sample = non-outage hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	1e-04	-0.0032			
	(2.6e-04)	(0.00055)			
RD_h (GWh)	0.0101	0.0103	0.0095	0.0096	0.0107
	(0.00026)	(0.00026)	(0.00026)	(0.00026)	(0.00028)
$W_{RES,h,n}$ (GWh)		0.11			
		(0.016)			
Solar_h (GWh)			0.0022	0.000	0.002
			(0.00026)	(0.00069)	(0.0007)
Wind_h (GWh)			-0.0077	-0.006	-0.007
			(0.00036)	(0.00084)	(0.00084)
$W_{solar,h,n}$ (GWh)				0.08	-0.04
				(0.021)	(0.021)
$W_{wind,h,n}$ (GWh)				-0.06	-0.06
				(0.026)	(0.027)
$X_{hydro,h,n}$					9.6
					(0.28)
$X_{therm,h,n}$					-2.3
					(0.57)
Num.Obs.	1100098	1100098	1100098	1100098	1100098
R2	0.115	0.115	0.116	0.116	0.116

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Nominal MOC - Full sample - $\gamma = 0.5$

Dependent Variable:	Is nominal MOC binding? ($\gamma = 0.5$, sample = all hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	0.00542	0.0056			
	(4.4e-05)	(9.4e-05)			
RD_h (GWh)	-0.00501	-0.00501	-0.00507	-0.00507	-0.00507
	(3.9e-05)	(3.9e-05)	(0.00004)	(0.00004)	(0.00004)
$W_{RES,h,n}$ (GWh)		-0.008			
		(0.0047)			
Solar_h (GWh)			0.00566	0.0044	0.0045
			(4.8e-05)	(0.00013)	(0.00013)
Wind_h (GWh)			0.00478	0.0057	0.0055
			(4.7e-05)	(0.00013)	(0.00013)
$W_{solar,h,n}$ (GWh)				0.07	0.06
				(0.0073)	(0.0073)
$W_{wind,h,n}$ (GWh)				-0.05	-0.04
				(0.0066)	(0.0066)
$X_{hydro,h,n}$					-18
					(1.3)
$X_{therm,h,n}$					-11.6
					(0.38)
Num.Obs.	4909632	4909632	4909632	4909632	4909632
R2	0.043	0.043	0.043	0.043	0.043

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Other MOC - Full sample - $\gamma = 0.5$

Dependent Variable:	Is MOC binding for other reasons? ($\gamma = 0.5$, sample = all hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	-0.0011	-0.0012			
	(0.0002)	(0.0005)			
RD_h (GWh)	0.0073	0.0073	0.0069	0.0069	0.0069
	(0.00021)	(0.00021)	(0.00021)	(0.00021)	(0.00021)
$W_{RES,h,n}$ (GWh)		0.01			
		(0.0255)			
Solar_h (GWh)			2e-04	-0.007	-0.007
			(0.00021)	(0.00074)	(0.00074)
Wind_h (GWh)			-0.0062	0.001	0.003
			(0.00029)	(0.00074)	(0.00075)
$W_{solar,h,n}$ (GWh)				0.40	0.43
				(0.04)	(0.04)
$W_{wind,h,n}$ (GWh)				-0.42	-0.50
				(0.038)	(0.038)
$X_{hydro,h,n}$					-1.97e+03
					(59)
$X_{therm,h,n}$					-3.0e+02
					(29)
Num.Obs.	1760696	1760696	1760696	1760696	1760696
R2	0.070	0.070	0.071	0.071	0.071

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Nominal MOC - $\gamma = 0.25$

Dependent Variable:	Is nominal MOC binding? ($\gamma = 0.25$, sample = non-outage hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	0.0085	0.0079			
	(6.8e-05)	(0.00015)			
RD_h (GWh)	-0.00765	-0.00762	-0.00777	-0.00777	-0.0080
	(5.8e-05)	(5.8e-05)	(5.9e-05)	(0.00006)	(6.2e-05)
$W_{RES,h,n}$ (GWh)		0.018			
		(0.0045)			
Solar_h (GWh)			0.0090	0.0088	0.0088
			(7.4e-05)	(0.00017)	(0.00017)
Wind_h (GWh)			0.0074	0.0074	0.0068
			(7.1e-05)	(0.00023)	(0.00023)
$W_{solar,h,n}$ (GWh)				0.006	0.014
				(0.0051)	(0.0051)
$W_{wind,h,n}$ (GWh)				0.00	0.03
				(0.0080)	(0.0083)
$X_{hydro,h,n}$					-0.7
					(0.062)
$X_{therm,h,n}$					-0.9
					(0.11)
Num.Obs.	3188823	3188823	3188823	3188823	3188823
R2	0.070	0.070	0.071	0.071	0.071

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Nominal MOC - $\gamma = 0.75$

Dependent Variable:	Is nominal MOC binding? ($\gamma = 0.75$, sample = non-outage hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	0.0085	0.0084			
	(6.8e-05)	(0.0001)			
RD_h (GWh)	-0.00765	-0.00764	-0.00777	-0.00776	-0.00791
	(5.8e-05)	(5.8e-05)	(5.9e-05)	(5.9e-05)	(0.00006)
$W_{RES,h,n}$ (GWh)		0.003			
		(0.0026)			
Solar_h (GWh)			0.0090	0.0085	0.0085
			(7.4e-05)	(0.00013)	(0.00013)
Wind_h (GWh)			0.0074	0.0076	0.0077
			(7.1e-05)	(0.00013)	(0.00013)
$W_{solar,h,n}$ (GWh)				0.017	0.022
				(0.0035)	(0.0036)
$W_{wind,h,n}$ (GWh)				-0.009	-0.007
				(0.0038)	(0.0038)
$X_{hydro,h,n}$					-0.47
					(0.022)
$X_{therm,h,n}$					-0.70
					(0.056)
Num.Obs.	3188823	3188823	3188823	3188823	3188823
R2	0.070	0.070	0.071	0.071	0.071

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Other MOC - $\gamma = 0.25$

Dependent Variable:	Is MOC binding for other reasons? ($\gamma = 0.25$, sample = non-outage hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	1e-04	-0.003			
	(2.6e-04)	(0.00074)			
RD_h (GWh)	0.0101	0.0103	0.0095	0.0095	0.0108
	(0.00026)	(0.00027)	(0.00026)	(0.00027)	(0.00029)
$W_{RES,h,n}$ (GWh)		0.10			
		(0.023)			
Solar_h (GWh)			0.0022	0.003	0.005
			(0.00026)	(0.00086)	(0.00086)
Wind_h (GWh)			-0.0077	-0.008	-0.006
			(0.00036)	(0.0013)	(0.0013)
$W_{solar,h,n}$ (GWh)				-0.04	-0.15
				(0.027)	(0.027)
$W_{wind,h,n}$ (GWh)				0.01	-0.10
				(0.0412)	(0.043)
$X_{hydro,h,n}$					20.3
					(0.57)
$X_{therm,h,n}$					-11
					(0.81)
Num.Obs.	1100098	1100098	1100098	1100098	1100098
R2	0.115	0.115	0.116	0.116	0.116

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Other MOC - $\gamma = 0.75$

Dependent Variable:	Is MOC binding for other reasons? ($\gamma = 0.75$, sample = non-outage hours)				
Model:	(1)	(2)	(3)	(4)	(5)
RES_h (GWh)	1e-04	-0.0025			
	(2.6e-04)	(0.00043)			
RD_h (GWh)	0.0101	0.0102	0.0095	0.0096	0.0102
	(0.00026)	(0.00026)	(0.00026)	(0.00026)	(0.00028)
$W_{RES,h,n}$ (GWh)		0.08			
		(0.011)			
Solar$_h$ (GWh)			0.0022	-8e-04	0.0013
			(0.00026)	(0.00055)	(0.00056)
Wind$_h$ (GWh)			-0.0077	-0.006	-0.007
			(0.00036)	(0.00064)	(0.00064)
$W_{solar,h,n}$ (GWh)				0.10	0.01
				(0.016)	(0.0161)
$W_{wind,h,n}$ (GWh)				-0.06	-0.04
				(0.018)	(0.018)
$X_{hydro,h,n}$					5.7
					(0.19)
$X_{therm,h,n}$					-1.3
					(0.41)
Num.Obs.	1100098	1100098	1100098	1100098	1100098
R2	0.115	0.115	0.116	0.116	0.116

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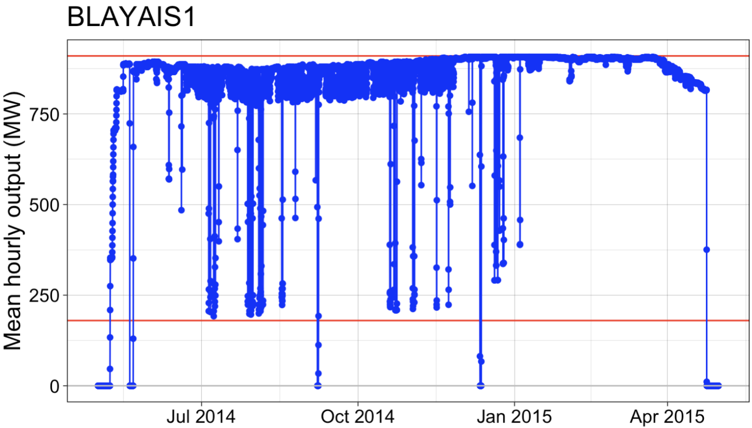
Example of fuel cycle



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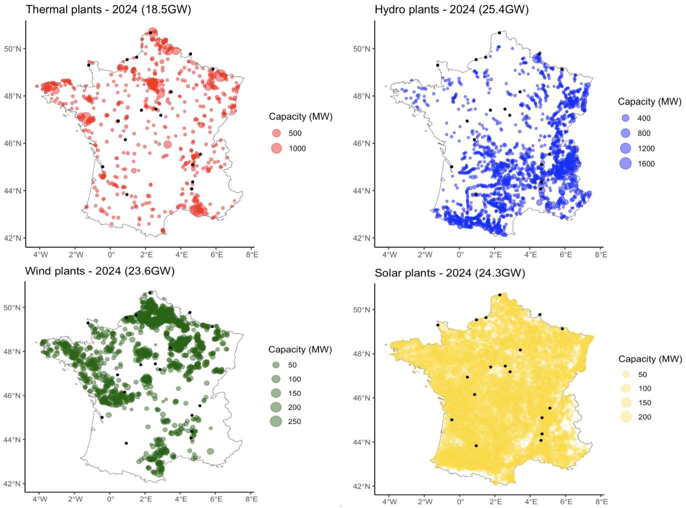
Location of nuke vs other facilities (31 Dec 2024)



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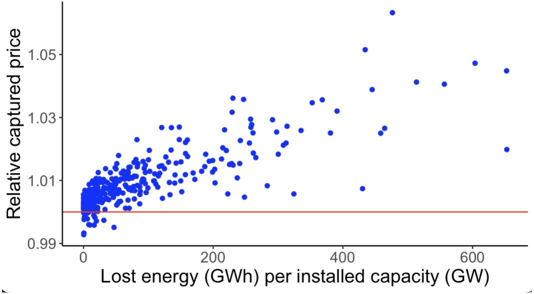
Captured price during the fuel cycle

We define, over non-outaged hours of each fuel campaign:

$$\text{Relative captured price} = \frac{\text{Average of spot prices weighted by output}}{\text{Unweighted average of spot prices}}$$



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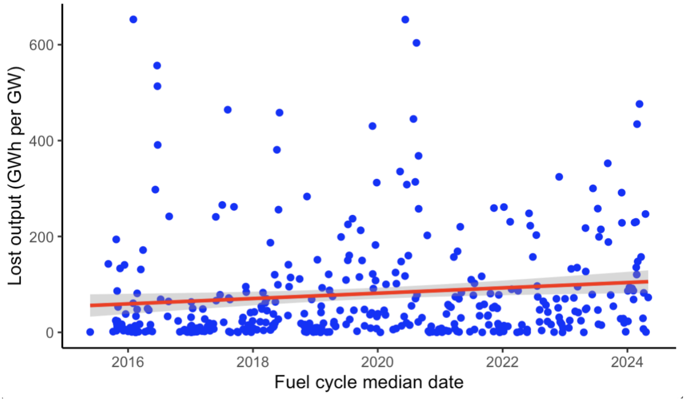
Time trend of lost energy per cycle-GW



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Partial Maximum Likelihood Estimation

Parameters θ are estimated by maximizing the following partial likelihood function:

$$L_1(\theta) \equiv \Pi_{i=1}^{n} \frac{\exp(\theta^T x_i(\tau_i))}{\sum_{l \in R(\tau_i)} \exp(\theta^T x_l(\tau_i))}$$

where:

- i indexes all observed dates τ_i of emergency events
- $R(\tau_i)$ denotes the "risk set" at τ_i, that is, all observations for which an emergency event either occurs at a later date or does not happen before the end of the fuel cycle (censoring).

Underlying intuition: most of the identification power for θ comes from "which" unit experiences an event (conditionally on an event occurring) rather than "when" the event occurs.

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