

EAERE, 2021

Strategies for short-term intermittency in long-term scenarios in the French power system

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Motivation & Findings

1. How scenarios account for **short-term** nuclear power flexibility?

Usual communication limited to Power and Energy or Capacity Factors. Need of details on cycling, speed, rated Pmin.

2. What **speed of ramping** of nuclear reactors?

Socially: the faster the reactor, the better. Privately: no need to hurry, loss of inframarginal rents, less profits.

3. What level of **minimum rated power** threshold?

Little sensitivity from 50% Pmin to 20% Pmin at low nuclear share.

4. What schedule **Baseload - Flexible** nuclear fleet?

Large Baseload (> 50% Fleet): more gas, inframarginal rents, more money.

5. What arbitrage Energy vs Capacity for attaining 50% nuc in 2035?

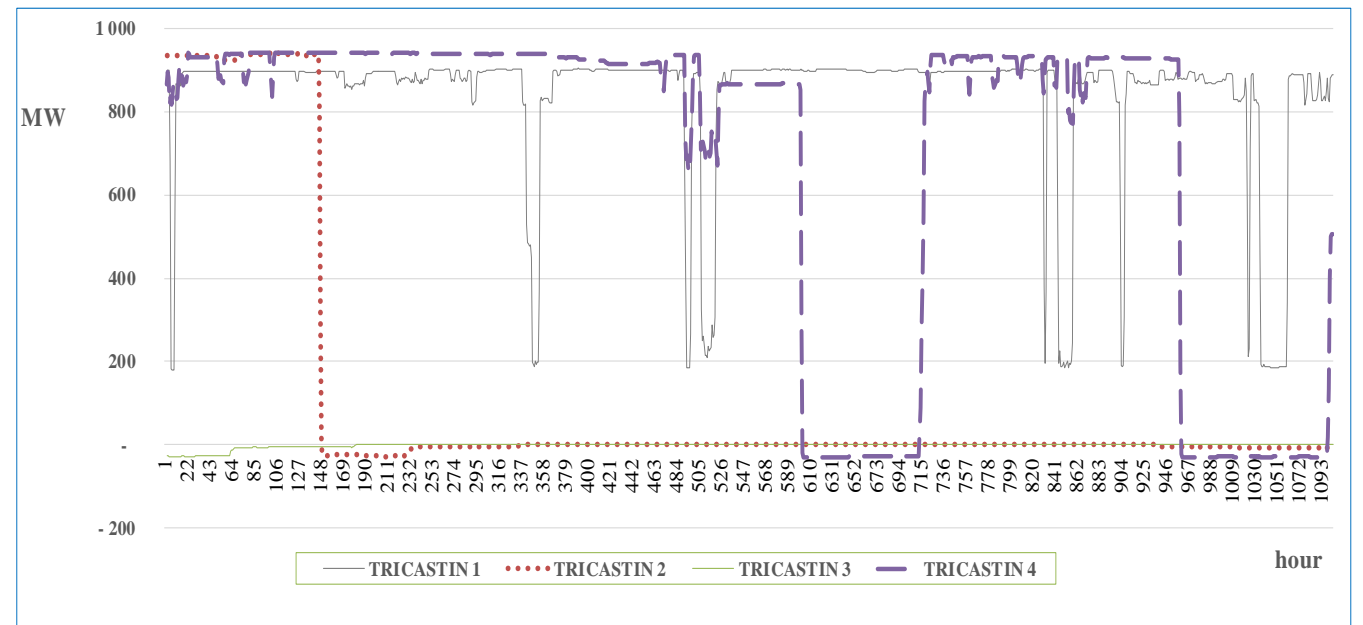
- Phasing-out nuclear **Power** (= 14 reactors): more gas needed, more pressure on flexible reactors. Less employment.
- Reducing **Energy**: reasoning in flows makes more sense, as large needs of capacities during winter and nights.

The Problem: How to align short-run (30 minutes) operation with long-run (30 years+) planning?

Agenda

- 1. Flexibility in electricity scenarios
- 2. Methodology: coupling models
- 3. Model results. Tests
- 4. Concluding remarks

Fig 1. Operation of nuc plant Tricastin over covid-19 lock-down in **March 2020**



Source: Based on RTE data, ECO2mix.

1. How scenarios account for nuclear power flexibility?

Intuition: Results with high temporal resolution models are in general different from long-term models due to the mismatch between data on constraints and on wind and solar inflows (Poncelet et al., 2004).

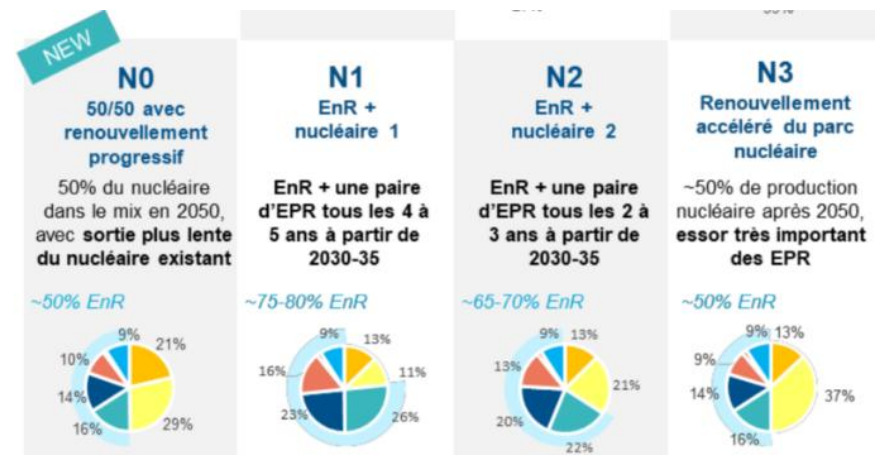
Coupling.

- Investment – dispatching TIMES-ANTARES (Alimou et al., 2020) - technology constraints, ramping.
- Planning – Dispatching POLES-EUCAD (Després et al., 2017) - storage in support to vRES.
- Planning – Grid expansion POLES-Network (Allard et al., 2020).

Contribution to nuclear flexibility: focus on the management of the nuclear fleet (Baseload versus Load-Following), speed of adjustment, min rated power, mix diversification, usage of capacities.

The future of nuclear power in France: under consideration (RTE, 2021).

- 8 scenarios to decarbonize the French economy
- Nuclear from 0% to 50% (new EPR + old LTO)



2. Methodology: Soft-linking one-direction coupling

- POLES: long-term planning
- EconUK: short-term operation

Nuclear Fleet Management:

% baseload, % load-following

Uranium use / Capacity Factors:

baseload CF, load-following CF

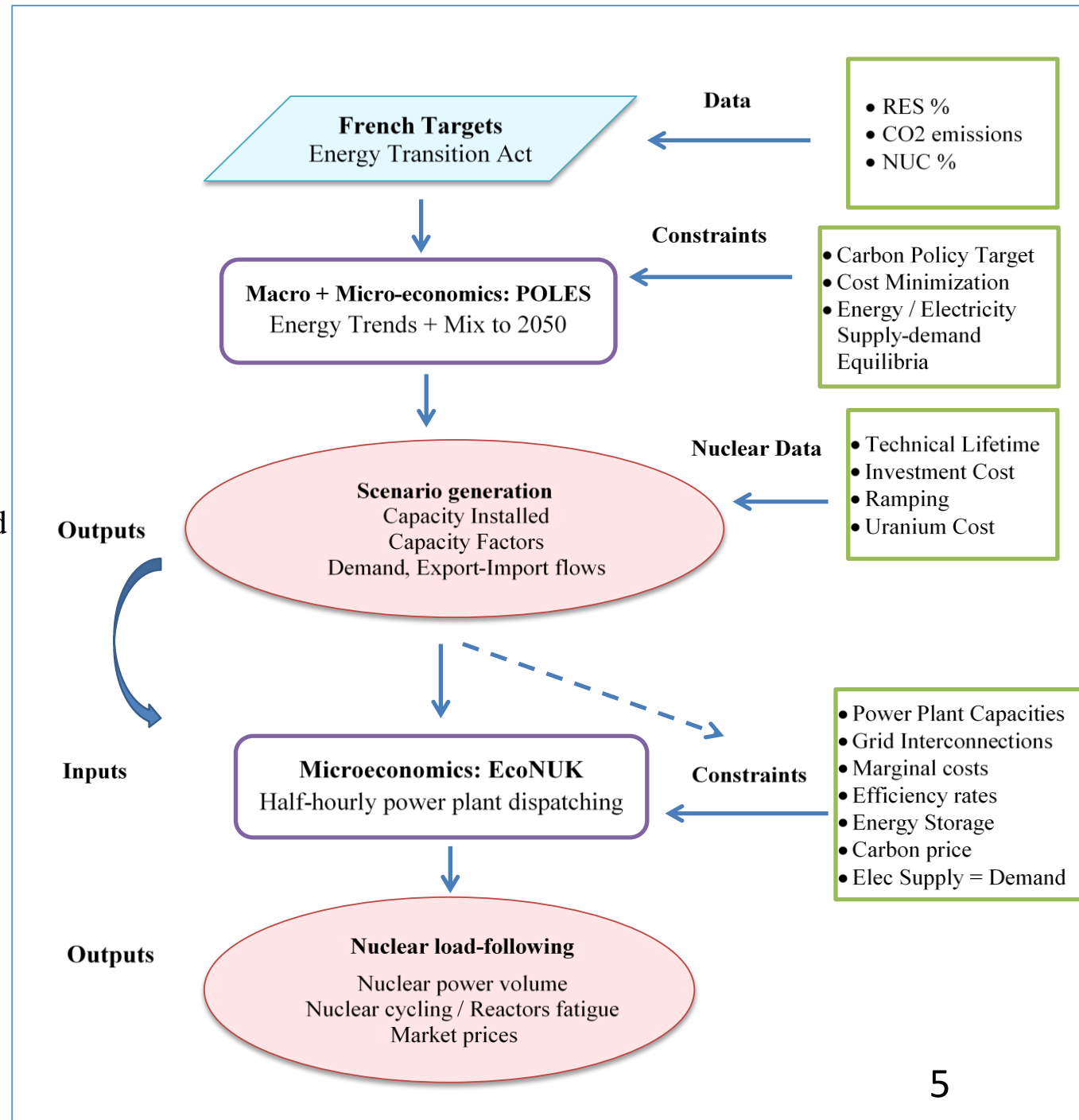
Ramping of nuclear reactors:

optimal versus actual

Minimum Operation Threshold

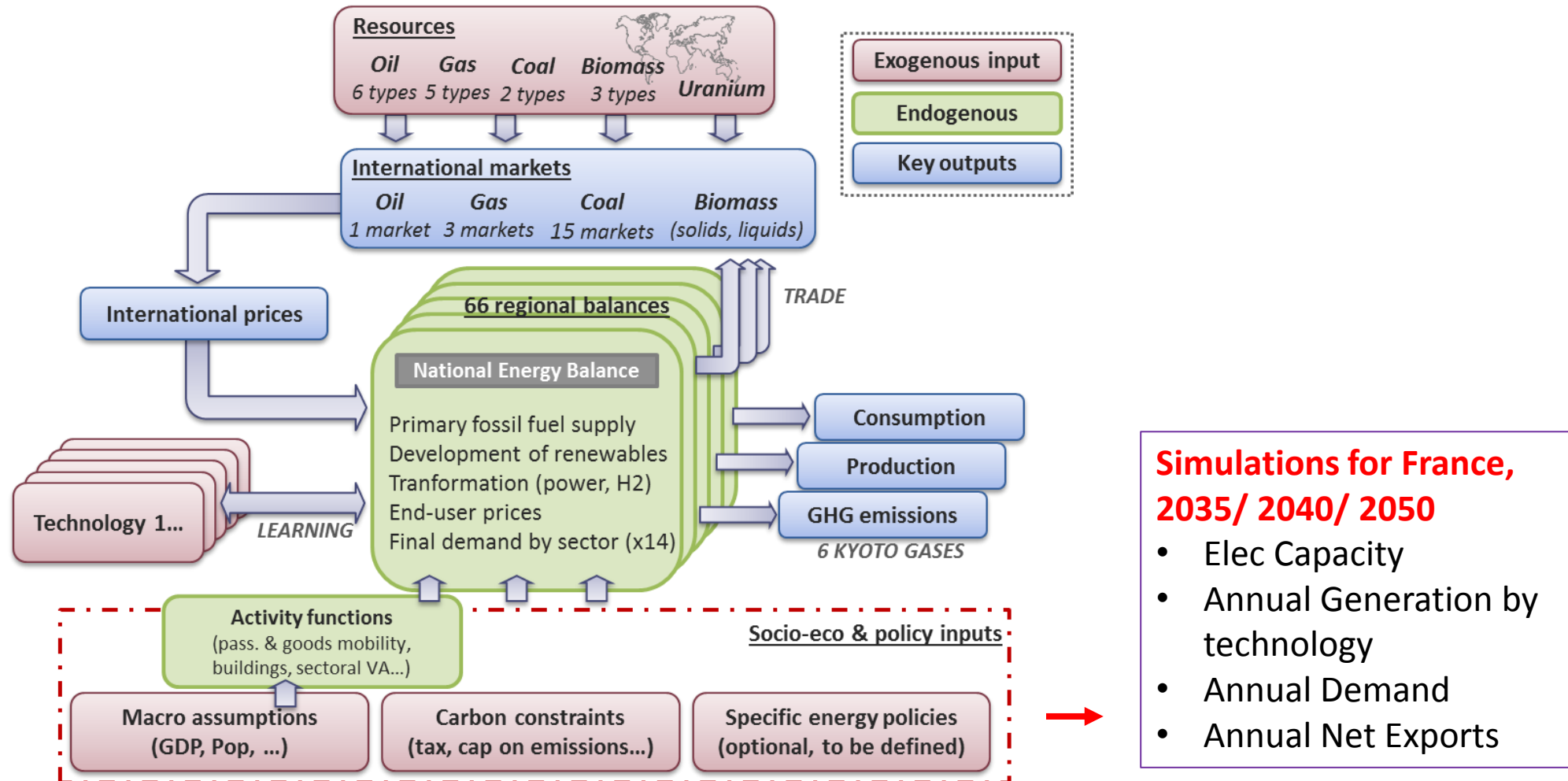
20%-50% P_{nominal}

Aggregated
results



POLES 2°C Scenario 2100 description

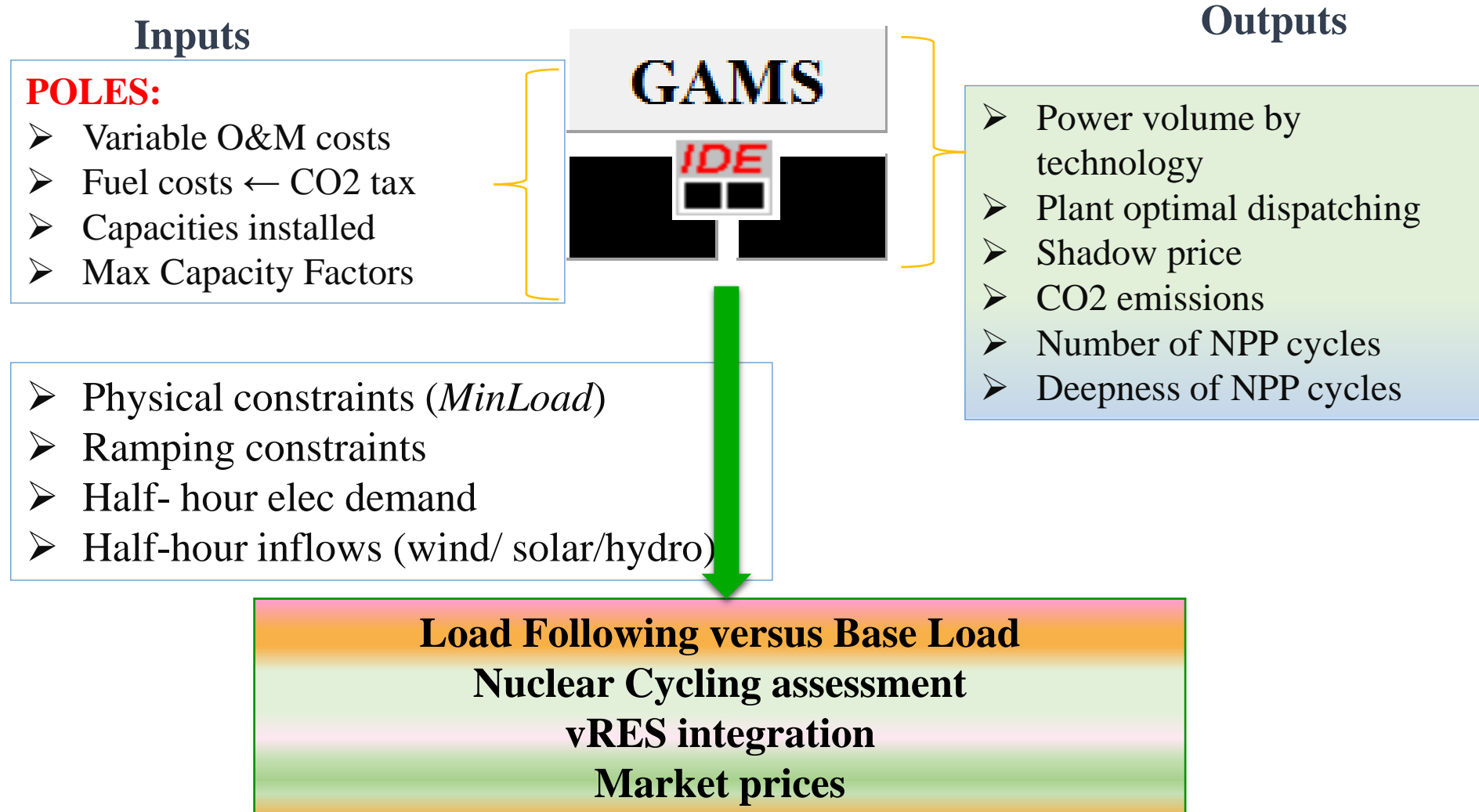
Prospective Outlook on Long-term Energy Systems



Simulations for France, 2035/ 2040/ 2050

- Elec Capacity
- Annual Generation by technology
- Annual Demand
- Annual Net Exports

Dispatching (*EcoNUK*) Market interaction



EcoNUK model description

Power plants **dispatching model**: Partial equilibrium dynamics (LP, Gams)

Eq Objective function = **Short-run System costs minimisation**:

$$Fobj = \sum_{h=1}^{8760} \left[P_M \cdot M_h + \sum_{tech=1}^{12} Gen_{h,tech} \left(Cvom_{tech} + \frac{Cfuel_{tech} + TaxCO2 \times cf_{tech}}{Eff_{tech}} \right) \right]$$

Eq Hourly power market **equilibrium Supply = Demand**:

$$\sum_{tech=1}^{12} Gen_{h,tech} + M_h + Sout_h = (D_h + X_h)/(1 - \tau^{loss}) + Sin_h$$

Eq **Availability** constraints:

$$Gen_{h,tech} \leq LF_{h,tech} AF_{tech} K_{tech}$$

Eq **Ramping** constraints:

$$1 - \tau_{tech}^{rampdown} < \frac{Gen_{h+1,tech}}{Gen_{h,tech}} < 1 + \tau_{tech}^{rampup}$$

Load Following

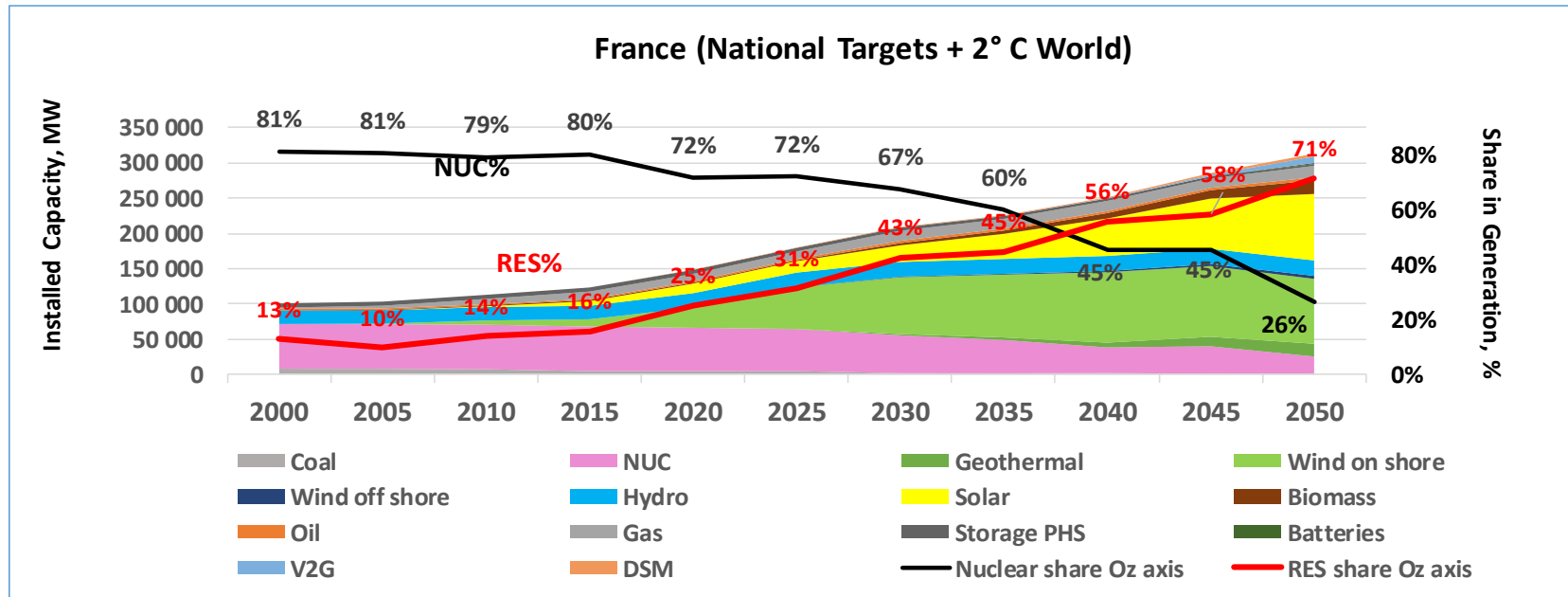


Eq **Minimum load** condition:

$$Gen_{h,tech} \geq MinLoad_{h,tech} LF_{h,tech} AF_{tech} K_{tech}$$

Eq **Storage** dynamics: $St_{h+1} = St_h + Sin_h \times Eff_s - \frac{Sout_h}{Eff_s}$

Long-term Scenario: TSO RTE Ampere 2035 + 2°C world 2100



POLES - in line with the French Energy Transition Act to 2035 s.t. 2°C by 2100 world level:

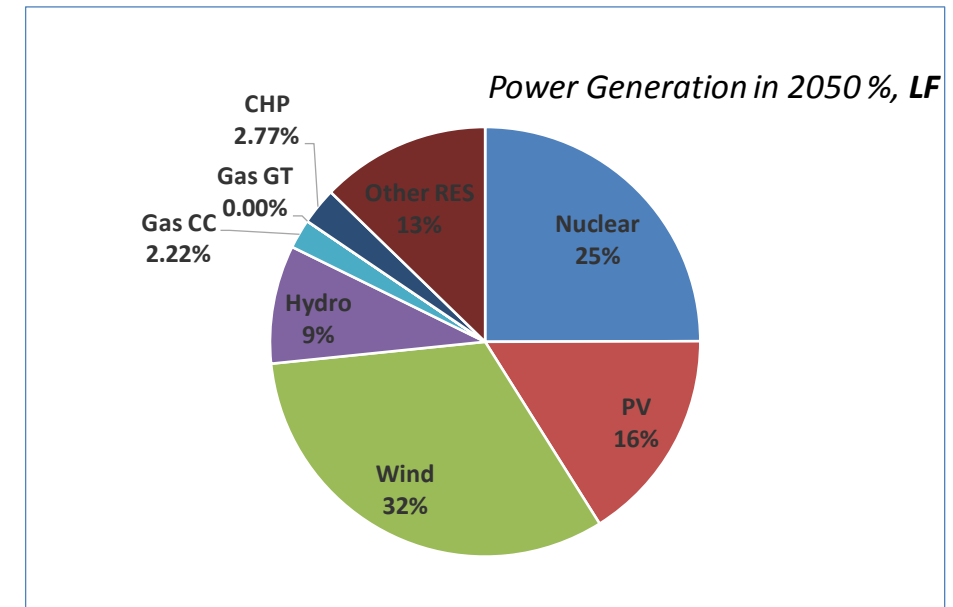
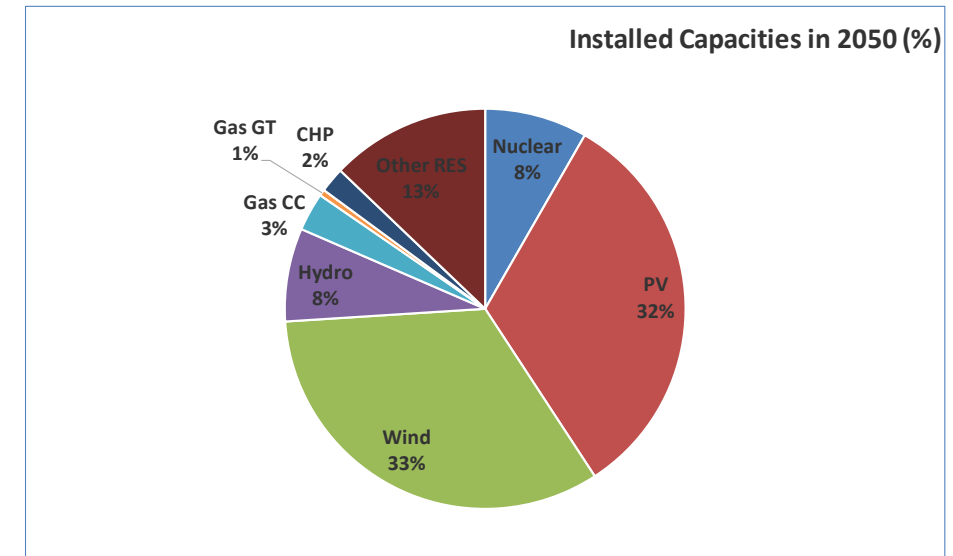
- 50% nuclear in 2035
- > 40% renewables in 2030
- zero net emissions by 2050.

Short-term Scenario: The French power mix in 2050

- **24 GW nuclear capacity** = 80 % Off-peak Demand
AND = 26% Peak Demand.
- **190 GW wind + solar** = 645% Off-peak Demand
AND = 208% Peak Demand

Assumptions of Ampere (RTE, 2017): Capacity and Power generation in 2050:

- coal power plants are phased-out
- combined heat-and-power capacity is reduced
- more gas-fired plants for capacity adequacy
- flexibility with DSM, exports, energy storage.



The higher the model **temporal resolution**, the higher system **flexibility needs**.

Scenario 2050, by model	POLES			EcoNUK	Δ
	Capacity	Generation	Capacity Factor	Generation	
Technology	MW	GWh	%	GWh	GWh
Nuclear	24 030	159 697	76%	159 697	0
Coal	1 369	6 613	55%	-	6 613
Oil	4 330	-	0%	1	-1
Gas	16 301	17 578	12%	31 912	-14 333
Hydropower	21 851	60 927	32%	56 988	3 939
Wind on-shore	91 929	192 293	24%	192 218	74
Wind off-shore	4 355	14 558	38%	14 490	68
PV Solar	94 240	106 376	13%	103 119	3 258
Other RES	37 289	81 484	25%	81 485	0
Total	295 694	641 175	25%	639 910	1 265
Curtailment (demand)	3 979	1 304	4%	1 394	-90
Storage (PHS + CAES + Batteries)	7 599	1 647	2%	10 475	-8 828
Interconnexion Imports, MW	27 000			27 000	0
Interconnexions Exports, MW	34 000			34 000	0
National Demand, GWh	471 478			471 478	0
Net export, GWh	54 611			54 611	0
Losses, GWh	115 085	17.9%		115 085	0
Nuclear / Generation	25%			25%	0%
Nuclear / Demand	34%			34%	0%
RES / Generation	71%			70%	1%
Variables RES / Demand	66%			88%	0%

Poles – EcoNUK:

At constant nuclear flows among the two models, more flexible gas flows in EcoNUK.

More curtailment of Renewables in EcoNUK

More DSM and storage in EcoNUK

Mix in 2035:

57% NUC + 42% RES = convenient combination for matching conventional generators with intermittent inflows: the curtailment of wind and solar energy is zero.

Table: Model results on flexible nuclear reactors

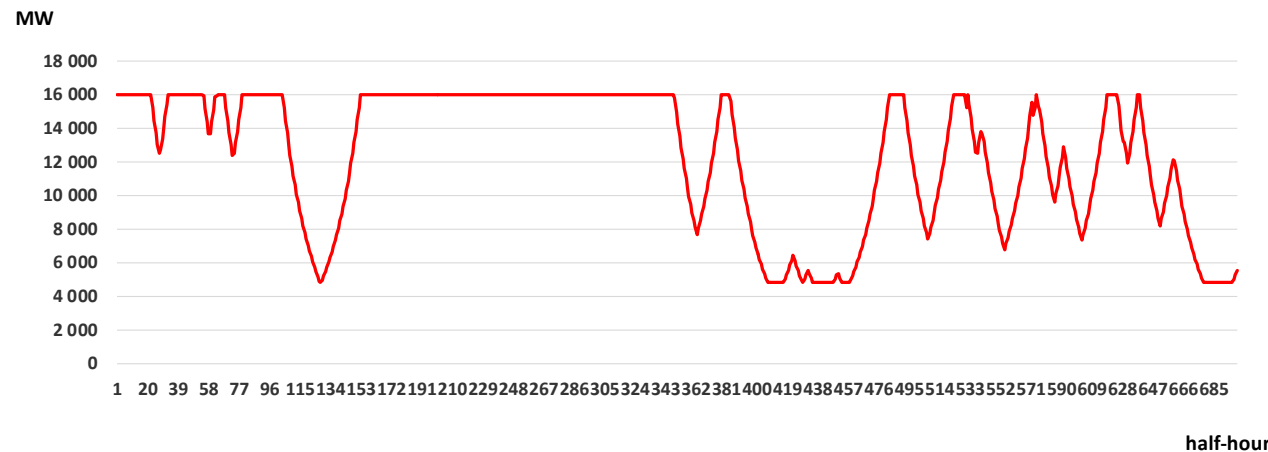
	Cycle Type		
Year	Light	Mid	Deep
2035	1 411	279	83
2040	601	167	179
2050	161	95	228

Cycle Type is the amplitude of load-following: light cycles in the range of 0%-20% of the nominal power (100%-80%-100%), mid cycles up to 40% (100%-60%-100%); deep cycles up to 70% of reactor rated power (100%-30%-100%).

Mix in 2050:

25% NUC + 65% vRES = deeper and longer flexibility than frequent short oscillations in 2035; excessive nuclear cycling (< 200 cycles /yr).

Nuclear Power flexible Fleet operation over two weeks in January 2050



Flexibility Adequacy: **an arbitrage** between flexible Nuclear and Gas

Coupling POLES-EcoNUK with constant gas flows (Sce_Gas) compared with constant nuclear flows (Sce_Nuc):

- more flexible nuclear power needed in EcoNUK compared to POLES (18 TWh).
- deeper ramping down and upper ramping replacing gas and eventually DSM measures.
- more nuclear light cycles (+8%) + deep cycles (+3%), budget of transient higher than the license.

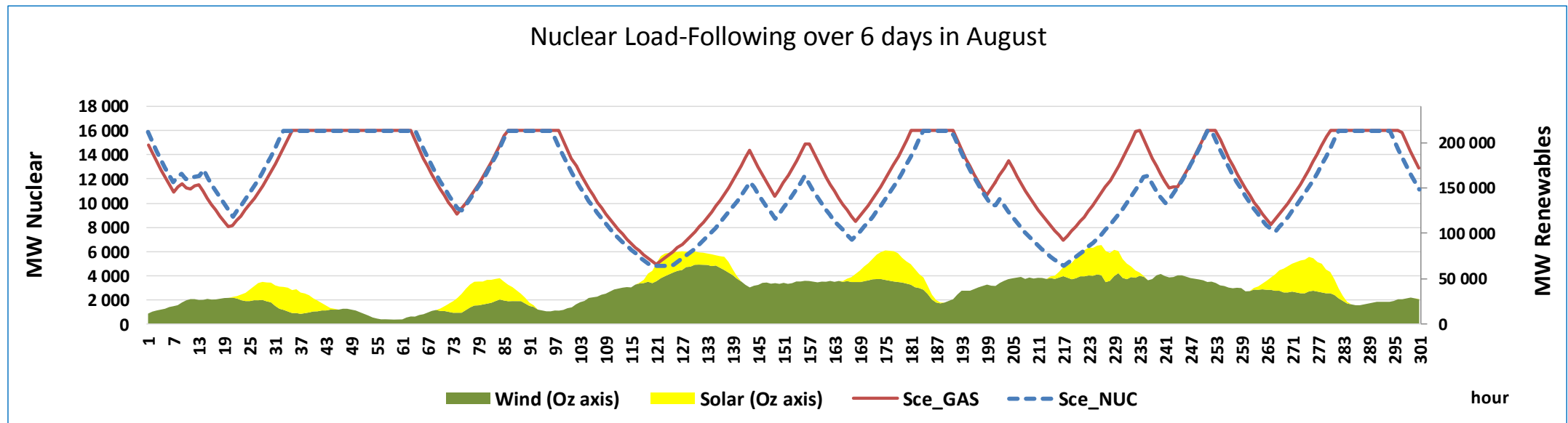


Fig. Flexible nuclear supply with model EcoNUK in 2050 in Scenario Gas_constant (Sce_Gas) and Scenario Nuclear_constant (Sce_NUC)

Test on ramping: System needs versus Nuc operator interests

	Baseline	Ramping			Minimum rated power		Baseload Share	
	Ramp 5% Pmin 30% BL 33%	1%/half-hour	10%/half-hour	20%/half-hour	20%	50%	10%	50%
Cycling								
Light	161	267	195	246	152	179	183	140
Mid	95	88	67	74	90	92	92	81
Deep	228	11	296	311	229	231	225	239
Capacity factors								
Baseload	71%	66%	68%	65%	73%	64%	62%	73%
Load-Following	78%	81%	80%	81%	78%	82%	77%	78%
Dispatching								
Gas, GWh	31 912	36 834	29 817	28 683	31 818	33 049	29 751	33 609
Storage, GWh	10 475	12 099	9 175	8 039	10 494	10 231	9 690	10 993
Curtailment, GWh	4 695	7 606	3 747	3 392	4 598	5 775	3 417	5 745
max VOLL, €/MWh	639	639	639	621	639	639	639	639

Faster reactors:

- more cycling (light+deep)

- higher CF for flex fleet

- less gas supply,

- less storage,

- less vRES curtailed

- less tensions on capacity market.

Tests on fleet management: Operating Flexibly or Base-load?

- More Baseload: more pressure on the remaining flexible capacity which has to cycle more; more vRES curtailment; more storage use.

Table: Marginal Technology, number of hours where the technology sets the price

Technology	10% Baseload	30% Baseload	50% Baseload
Renewables	0	0	0
Nuclear	3 891	2 915	2 372
Gas Turbines	4 188	5 201	5 745
Demand Side Management	679	642	640

Higher the Baseload share, more hours with gas = inframarginal rents for nuclear.

- More Load-Following: an eviction effect of the gas supply on the market (cannibalism effect).

	Cycle Type		
	Light	Mid	Deep
Baseload = 1/2 Fleet	140	81	239
Baseload = 1/3 Fleet	161	95	228

Nuc flexibility does not occur more often, but the magnitude of flexibility varies.

Test on availability. What if 1 GW reactor is out of operation over one year in 2050?

Q: Is the system able to face the risk of reactor unavailability?

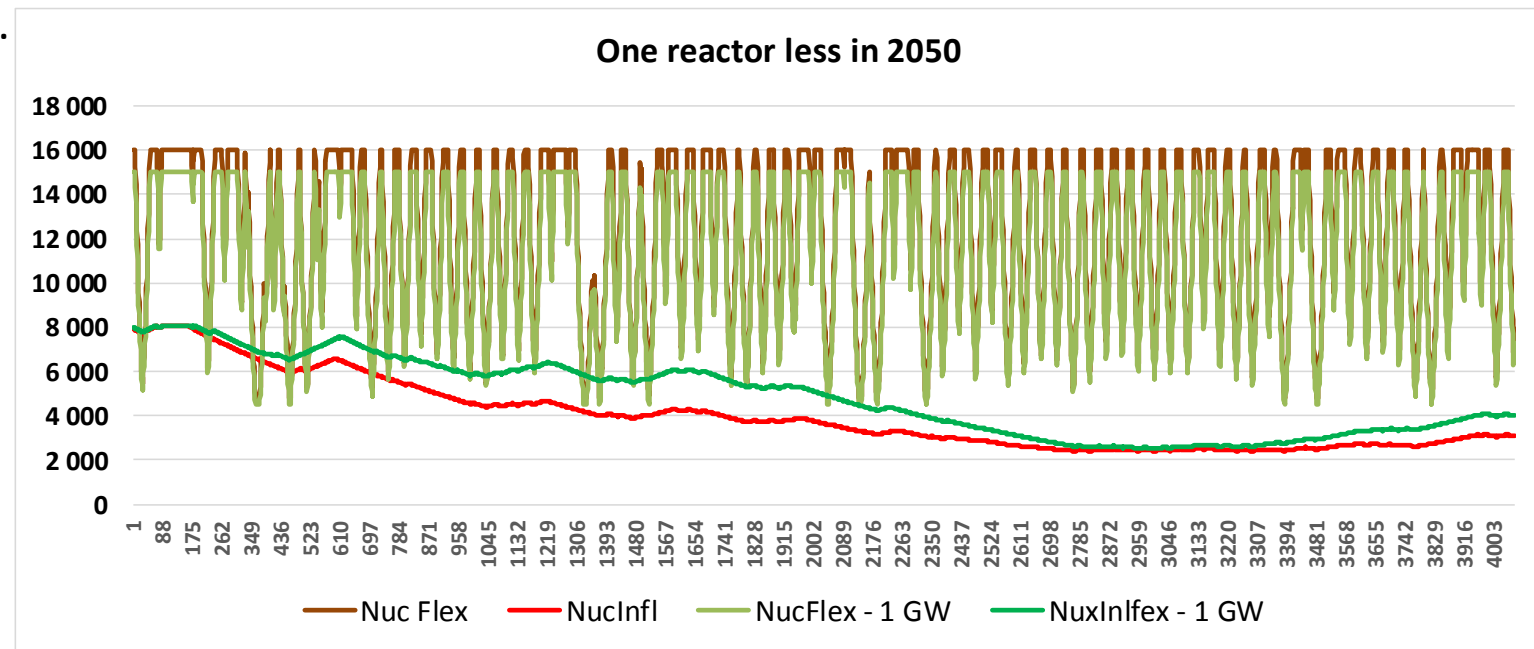
A: The system obtained with POLES for 2050 has the necessary capacity in EcoNUK (no increase in the shadow cost).

Substitution effects:

- Flows: More gas (+700 GWh) for ~ 4,000 hours.

- More vRES curtailed (-400 GWh).
- 1 MWh of nuclear replaced by gas + another operational reactor with spare capacity.
- Remaining fleet of reactors runs more: CF from 71% up to 80% for Base-Load; from 78% to 79% for Flexible fleet.

- Power: 1 GW nuclear less needs 1,740 MW more gas, due to ramping constraints of the remaining fleet to attain full power during positive flexibility requirements.



Concluding remarks

1) Planning. The trade-off for an energy planner is between Nuclear and Carbon target.

- Fulfilling nuclear reduced share target counterbalances the respect of carbon emissions limit, as more gas is necessary to ensure flexibility. Uncertainties on massive gas from H2 or with CCS: more GHG emissions.

2) Future reactor design. Excessive nuclear cycling indicates the need for faster reactors in the future.

- Revision of reactor transient limits would prevent early upgrading or retirement.

3) Fuel management. Accurately anticipating the Capacity Factor is key to optimally manage the fuel and to minimise the fuel cycle cost.

4) Flexibility provision. A market-based mechanism and a matter of central planning.

- Market signals: Irregular non-convexities due to ramping make deviate from long-term cost, hence, the marginal cost-based mechanism, specific to liberalized electricity markets, can discourage the investment in flexible technologies.

- Central planning of load-following (new O&M plant specifications, safety analysis, codes, standards, human resources for special controls and monitoring); inertia of historical load-following experience and instrumentation; new managerial routines.

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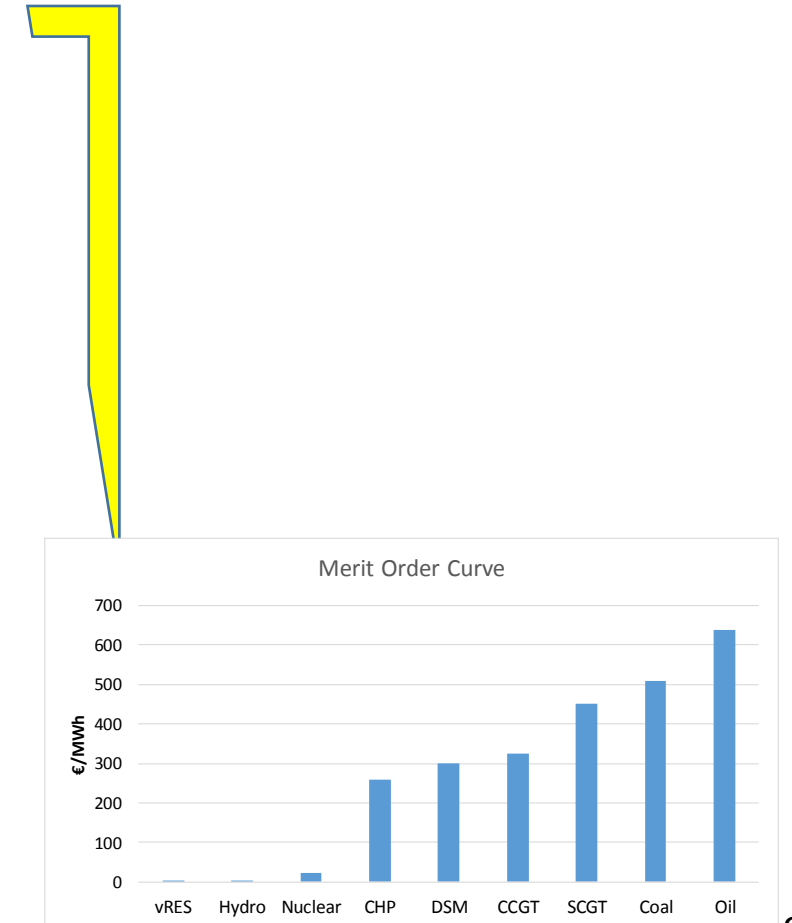
Thank you for your attention!

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POLES Climate Policy Scenario 2050

Inputs of the model, by technology type, in 2050				
Technology	Efficiency	Max Availability	Ramp	VOM CO2= 767 €/t
	%	%/year	%/half-hour	€/MWh
Nuclear Inflexible	36%	90%	0.1%	22
Nuclear Flexible	36%	90%	5%	22
Hydro River	100%	42%	100%	3
Hydro Lake	100%	28%	100%	3
Coal	40%	70%	25%	509
Oil steam turbine	41%	70%	50%	639
CCGT (Combined cycles gas	55%	80%	10%	324
NGGT (Natural gas gas turbines)	40%	100%	90%	452
CHP (Combined heat and power)	70%	70%	10%	258
Wind On-shore	100%	24%	100%	1
Wind Off-shore	100%	38%	100%	1
Solar	100%	13%	100%	1
Other RES	100%	25%	100%	1



Capacities for Flexibility

- **1. Flexible generation capacity**

- Gas Simple Cycle Gas Turbines
- Dispatchable renewables: Hydro power plants. Biomass fired plants. Geothermal plants
- Nuclear power plants
- Gas Combined Cycle Gas Turbines

- **2. Transmission capacity**

- Grid interconnection: Export - Import possibilities.

- **3. Storage capacity**

- PHS, CAES, H2, batteries.

- **4. Flexible demand**

- DSM, EV, H2.

NUC Load Following versus Base Load (= Steady State) – dispatching

Nuclear Load Following substitutes **Gas** and avoids some **RES** curtailment.

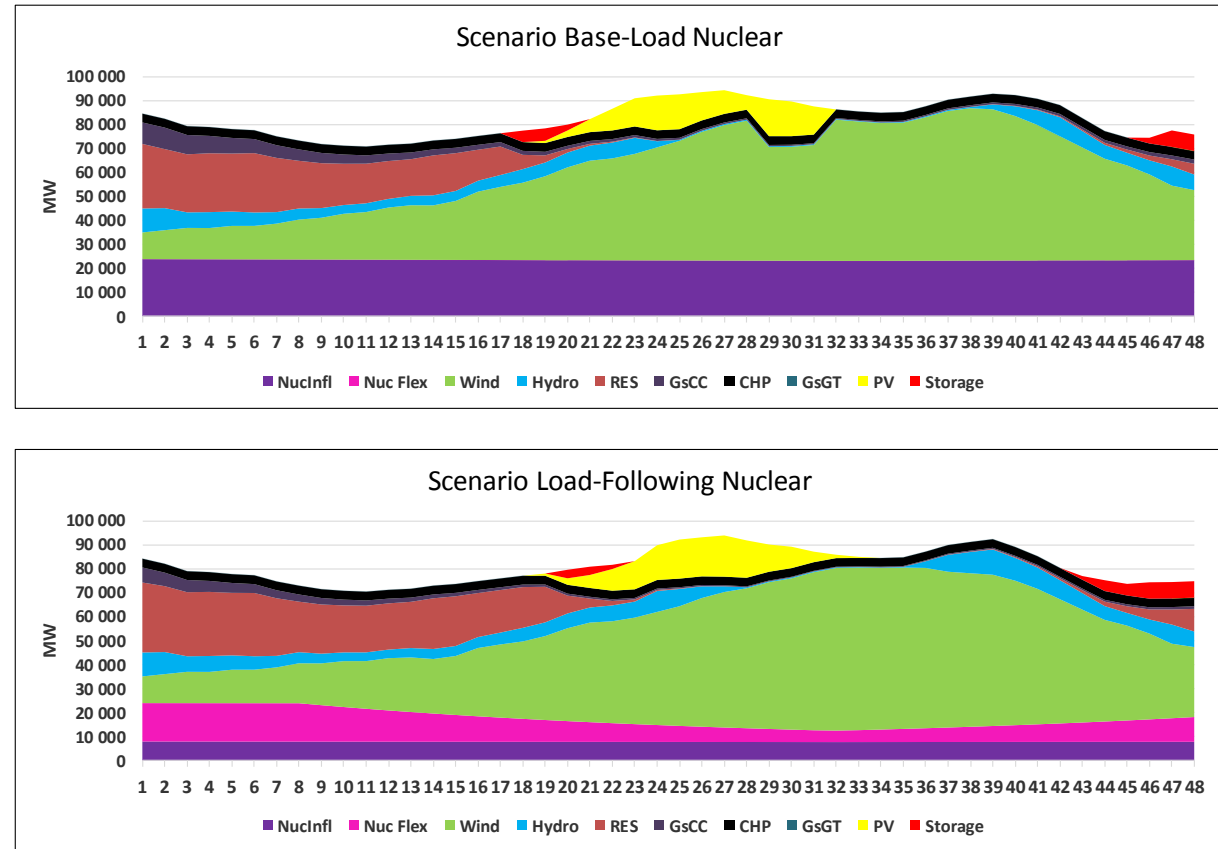


Fig. Comparison of load-following with baseload nuclear over one day in January 2050