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Market and social value of nuclear load-following in comparative scenarios

Nuclear - IRES 2030

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Context

Increasing IRES lead to **integration costs** (Hirth, 2015)

- Additional system costs:
  - Distribution and transmission costs
  - Balancing costs
  - Reserve margins
- Additional costs at the conventional power plant level:
  - cycling, turning off or part-load generation

Many studies investigate system cost effect + additional cost on **fossil fuel power plant**

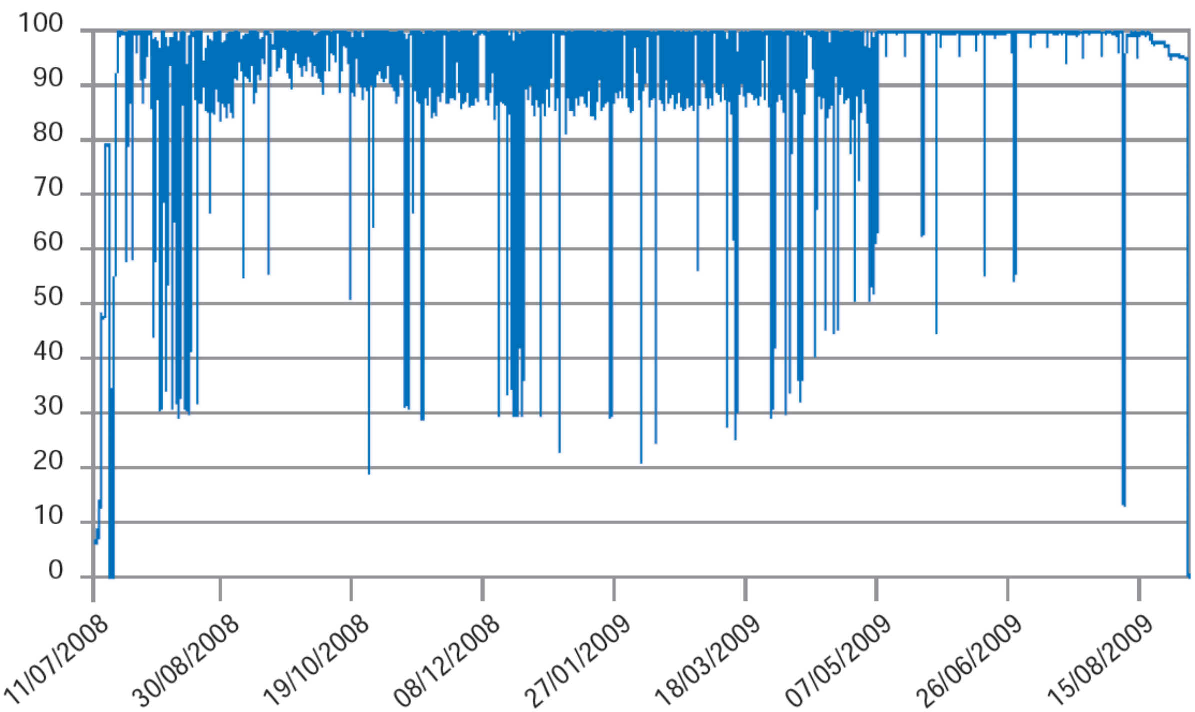
- Bertsch 2016; Goransson 2014; Kumar et al. 2012; NREL 2012, Nicolosi 2011, etc.

Only recently studies investigate **flexible capability of Nuclear PP**

- Cany et al. 2016, Gustavsson 2014, Persson et al. 2012, Keppler et al. 2012, OCDE-NEA 2011, Bruynooghe et al. 2010, Pouret & Nuttal 2010, Ludwig et al. 2010, etc.

Historical yearly operation of French a flexible nuclear power plant

Figure 3.3: **Example of the power history of a French PWR reactor engaged in load following**



Source: OCDE-NEA, 2012

https://www.oecd-nea.org/ndd/pubs/2012/7056-system-effects.pdf

Specific questions addressed

Are nuclear reactors flexible enough to meet political objectives of IRES and change NUC decommissioning path?

- Would additional load following impact the early retirement?

What is the additional flexibility needed by the system due to more intermittency?

- What is the cost/ benefit for a NPP operator to operate load-following?
- What is the value of the load-following compared to baseload operating mode?
- What are the benefits for the system?

Is nuclear load-following changing the path of IRES integration?

- Market volume selection by technology (IRES, NUC).
- Asset use rate. Hourly curtailment over the year.

Plan

1. Assessment of nuclear flexibility

- Cycling capability of a PWR reactor

2. Methodology

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3. Results analysis

- Projections in 2030

4. Policy options

- NPP operators
- Decision-makers

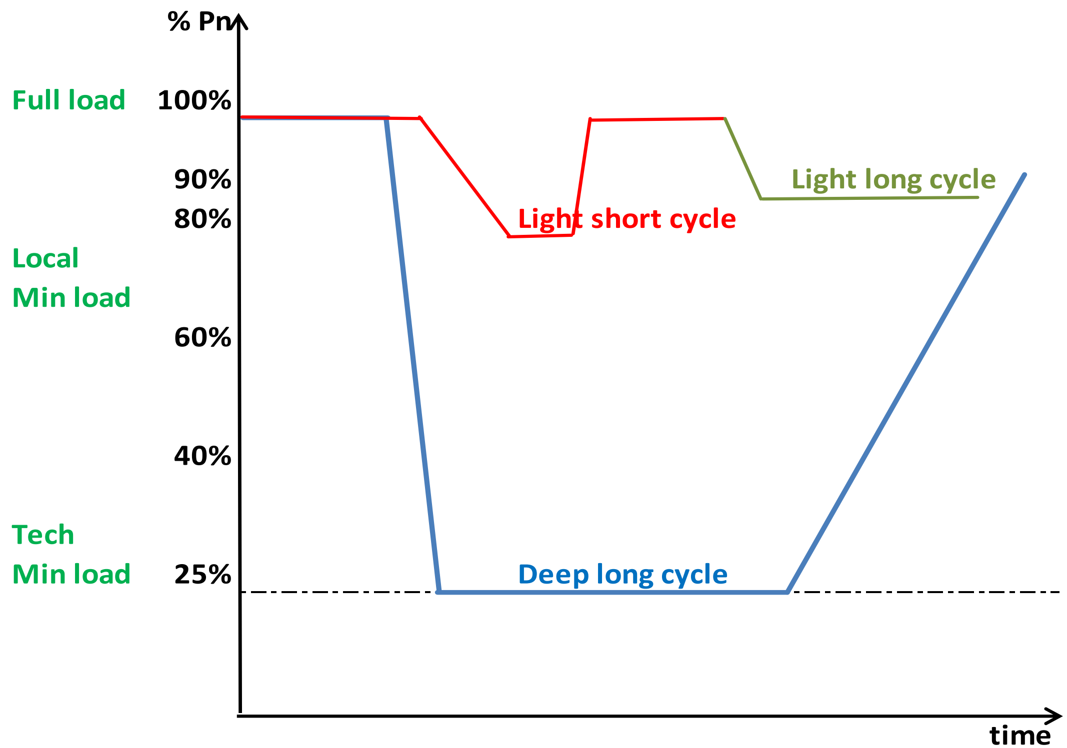
1. Assessment of nuclear flexibility

Load-Following is any change in the generation of electricity to match the expected electrical demand (>7%).

Regulatory Requirements: NPP must be capable of:
Minimum: daily load-cycling 100-50-100 Pn; speed 3-5 %/min Pn;
Maximum: 2 cycles/ day, 5 c/ week, 200 c/ year (EUR, 2012).

Cycling is measured by the transient from full power to local minimum load and back to full power.

Fig.1. Load-following capability of a PWR



1. Assessment of nuclear flexibility

Reactor licence provision

- The design of flexible nuclear reactors describes the maximum number of deep and light cycles, function of the amplitude of the power variation.

Load profiles (Areva, EPR):

- **Light** cycles, 100-60-100 Pn, speed 5%/min Pn
- **Deep** cycles, 100-25-100, 2.5%/min Pn.

PWR Konvoi reactor design, number-deepness of cycles

Load cycle (% power rate)	Number of cycles
100-90-100	100 000
100-80-100	100 000
100-60-100	15 000
100-40-100	12 000

Ludwig et al., 2010.

1. Assessment of nuclear flexibility

What are the costs of load following?

Cycling effect : unitary cycle cost seems to be very small if any (Keppler et al. 2012, Elforsk 2012, Bruynooghe et al. 2010).

- Maintenance costs: LF accelerates equipment ageing
- Fuel cost: no additional fuel cost if planned load following
- Training of personnel, staff costs: significant in IAEA (2015)
- *"with a well-prepared load-following, there are very few additional costs"* (Elforsk, 2012, p8).

Investment costs in flexible NPP: no additional cost in the French case as load-following already effective (PWR).

Compression effect: Decreased profits due to lower load factor.

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2.1. Energy Scenarios Survey

Data on the electric generation mix, demand, export-import flows, for France 2030 / 2050:

- **Regulator**: Scenario European Commission (EC, 2013)
- **TSO**: 4 scenarios from RTE (Bilan prévisionnel, 2014)
- **National Debate:** Scenarios DEC/DIV/EFF (Carbone 4, 2014)
- **Policy support Agency**: Vision ADEME 2030 / 2050 (2013)
- **Consultant**: Scenario UFE 2030 (UFE-Artelys, 2015)

Profusion of scenarios:

- **Demand**: 2012 - 487TWh; 2030 – 300TWh (Negawatt), 521TWh (Negatep)
- **Exports**: 2015 – 91TWh; 2030 – 5TWh (ADEME), 100TWh (RTE)
- **IRES** / final demand: 4% (2014); 2030 – 11% (RTE A), 74% (Negawatt)
- **NUC**: 75% (2012); 2030 – 18% (Negawatt), 83% (Negatep)

2.1. Scenario selection – 2030

Technology	RTE TSO Scenarios						ANCRE Scenario		
	Scenario low growth rates			Scenario new energy mix			DIVersification Path (ANCRE DIV)		
	Capacity, GW	Generation, TWh	LF	Capacity, GW	Generation, TWh	LF	Capacity, GW	Generation, TWh	LF
Nuclear	57.6	386.6	77%	37.6	254	77%	44	287	74%
Coal	1.7	10.2	68%	1.7	1.4	9%	0	0	-
Gas CCGT	5.4	11.4	24%	9.4	48.6	59%	12	44	43%
Oil, NGGT	4.4	0.1	0%	9.9	0.2	0.2%	12		
Decentralised CHP	5.4	12.9	27%	5.4	12.9		11.7		
Biomass	1.4	6	49%	1.8	9.5	60%	10	44	50%
Hydro	20.9	63.4	35%	20.9	64.9	35%	20	65	37%
Wind	21.7	48.2	25%	36.6	86.2	27%	43	89	24%
Solar	12.3	15.2	14%	24.1	29.7	14%	36	44	14%
Marine energy	0	0	-	3	8.6	33%	0	0	-
Total Supply	130.8	554	48%	150.4	507.4	39%	188	573	35%
PHS Storage	4.3		0%	6.3			5		
Demand		455			490			465	
Export		99			26			60	

2030 Scenario choice (Generation / final demand):

- **SCE1 RTE** – IRES 11%, NUC 70%.
- **SCE2 RTE** – IRES 22%, NUC 49%.
- **SCE3 ANCRE** – IRES 25%, NUC 55%.

2.2. Power Plant Dispatching model

Inputs

- Hourly power demand
- NPP cycling transient budget
- Technico-economic parameters
- Physical constraints
- Hourly natural inflows (wind/ solar)

GAMS IDE

Outputs

- Power volume generated by technology.
- CO2 emissions.
- Plant optimal dispatching
- Shadow price
- Number of NPP cycles
- Deepness of NPP cycles

LF Cost
System Cost
System Stability

2.2. Model description

A dispatching power plant model applies to the French market.

- Linear programming, GAMS software.
- Partial equilibrium dynamic model (8760 time slices).
- Fixed non constant power demand.
- Sensitivity to up/down extreme variations of residual load.
- Endogenous selection of technologies (merit order curve).

1. **Objective function**: **short-run system cost** min to operate generators.

Fobj = Costs_fuel + Costs_ CO2 + Costs_VOM + Costs_Import

2. Real-time power market equilibrium at every hour (in volume):

$$\sum_{tech=1}^{12} Generation_{h,tech} + Imports_h + Storage\_out_h = (Demand_h + Export_h)/(1-\tau^{loss}) + Storage\_in_h$$

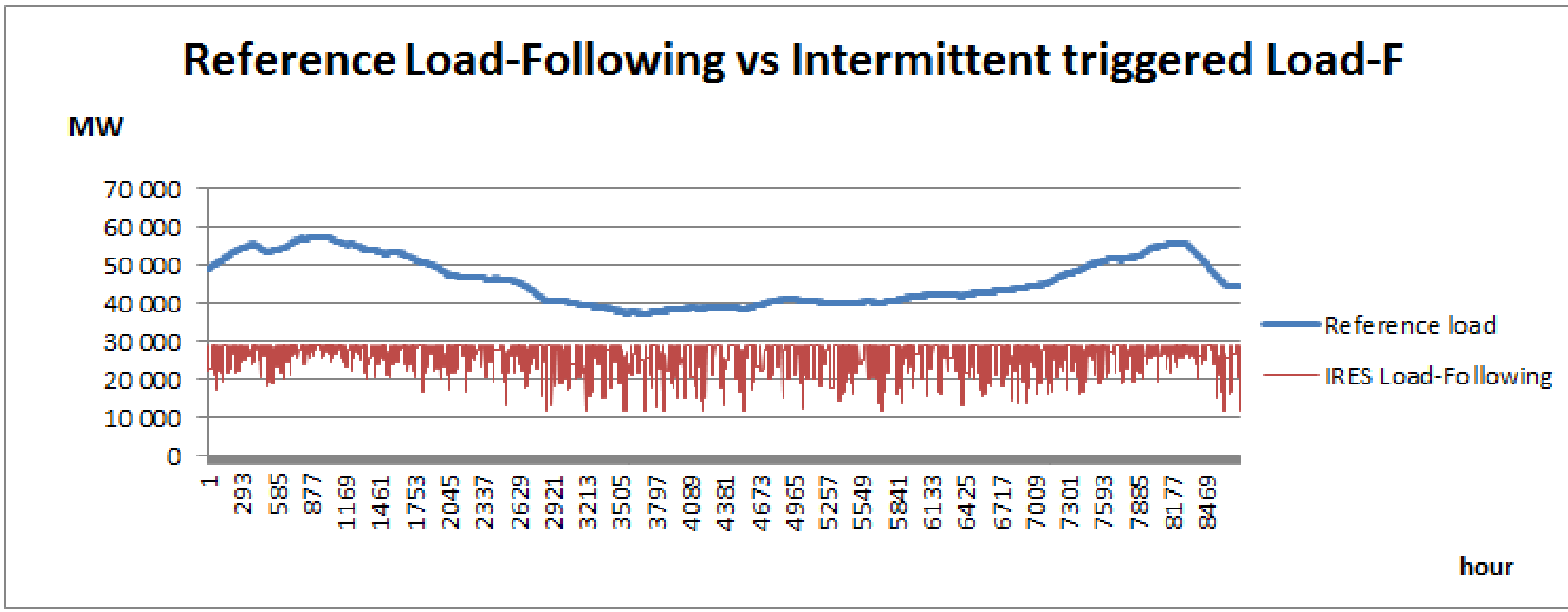
Model Inputs Picture

INPUTS, France 2030, RTE Low Growth Scenario							
Technology	Capacity	Efficiency	Fuel Cost	CO2	Max	O&M	Ramp
	MW	%	€/MWh	kg/kWh	%/year	€/MWh	%/hour
Nuclear	57 600	33%	8.2		0%	1.75	0.1% REF 100% LF
Coal	1 700	36%	18.1	0.34	0%	1.69	14%
Hydro	20 900	100%	0		35%	2.5	100%
Oil steam turbine	1 500	39%	63.4		0%	2.1	100%
CCGT	5 400	57%	36.2	0.20	0%	0.86	50%
NGGT	2 900	39%	36.2	0.20	0%	0.86	100%
Biomass	1 400	27%	40.0	0.36	0%	2.1	100%
CHP	5 400	35%	55.0	0.25	0%	8	50%
Wind On-shore	18 700	100%	0		18%	0	100%
Wind Off-shore	3 000	100%	0		35%		100%
Solar	12 300	100%	0		14%	0	100%
Other RES	-	100%	0	0.00	0%	0	100%
Total Capacity, MW	130 800						
Connections X-M, MW	23 000						
National Demand, TWh	455						
Export, TWh	100						
Losses, TWh	12						

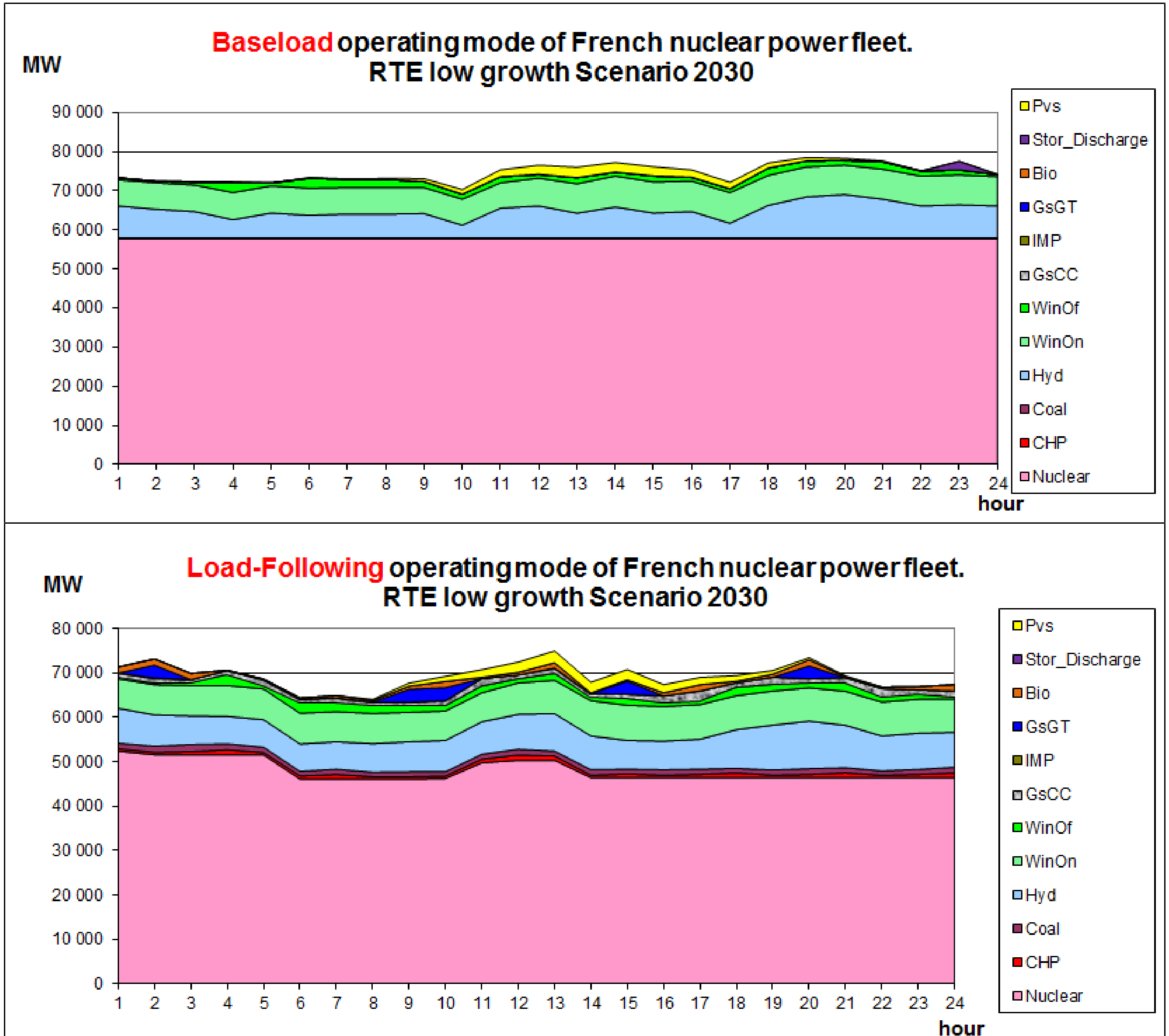
Model main technology assumptions

- Aggregated generators into 12 representative technologies.
- Restrictive ramping rates
- Nuclear Reactors cycling limit: 100-40-100 of rated power.

Reference case: historical load-following



Flexibility value: Comparison of Reference - Load-Following operating modes



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NUC operating constraints from IRES, Demand, Exports

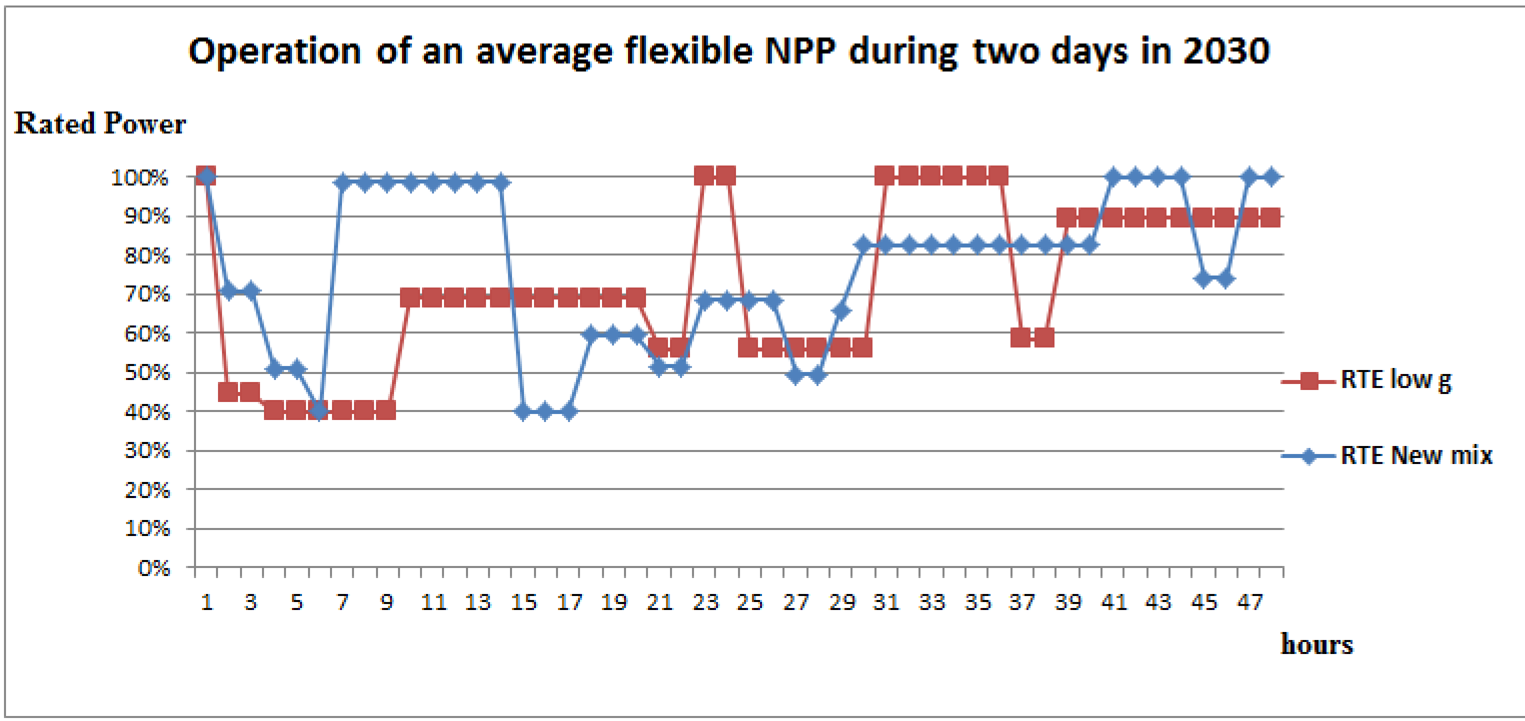
Uncertainty on expected results:

- ***RTE Low g***: low IRES shares, but higher than Min load NUC capacity. Consequence X are supposed to be higher, to sell the excess.
- ***ANCRE DIV***: highest IRES shares, high ratio NUC_K/Min Load, lower X.
- ***RTE New*** mix appears to be less stressful for Nuc power plants.

Scenario	Main Scenarios differences affecting Load-following					
	INPUTS				OUTPUTS	
	NUC, MW	Load, TWh	Min Load, MWh	Max Load, MWh	IRES, %	NUC, %
RTE Low g	57 600	455	28 730	95 157	10%	73%
RTE New mix	37 600	491	30 955	102 526	20%	49%
Ancre DIV	44 000	466	29 400	97 376	26%	54%

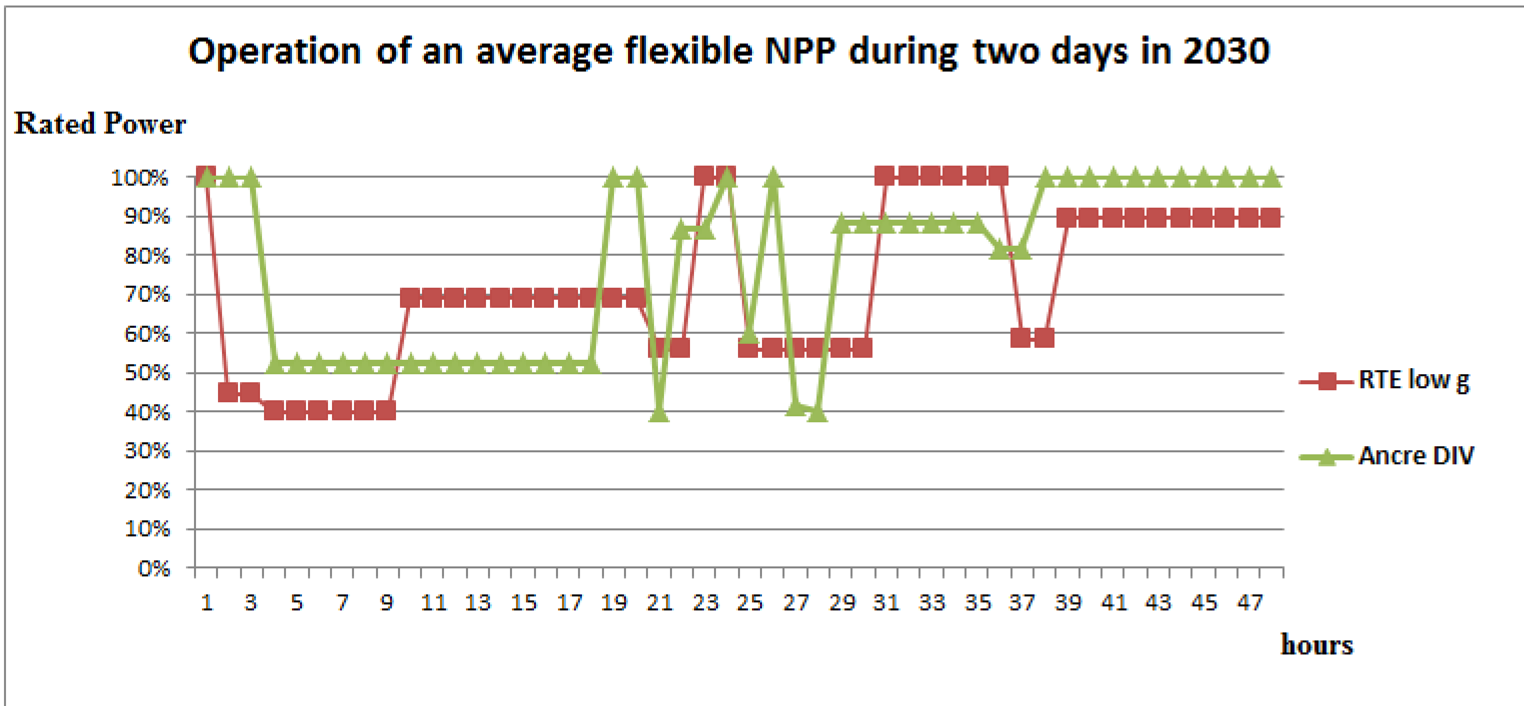
Excessive cycling of flexible NPP in RTE New mix SCE

- Additional plant fatigue in 2030 in RTE New mix / RTE Low growth.
- ***RTE new mix***: deeper more frequent cycles, due to more intermittency.
- ***RTE low growth***: longer NPP cycles (longer plateau effects).



Even more excessive cycling in ANCRE DIV scenario, Lower NPP load-factors

- More cycles in ANCRE DIV case (all short, deep types).
- Deep cycles (60% Kn) = 15% more in ANCRE DIV / RTE Low g.
- Less Nuc capacity, higher needs of flexibility.



Cycling budget statistics in ANCRE DIV:

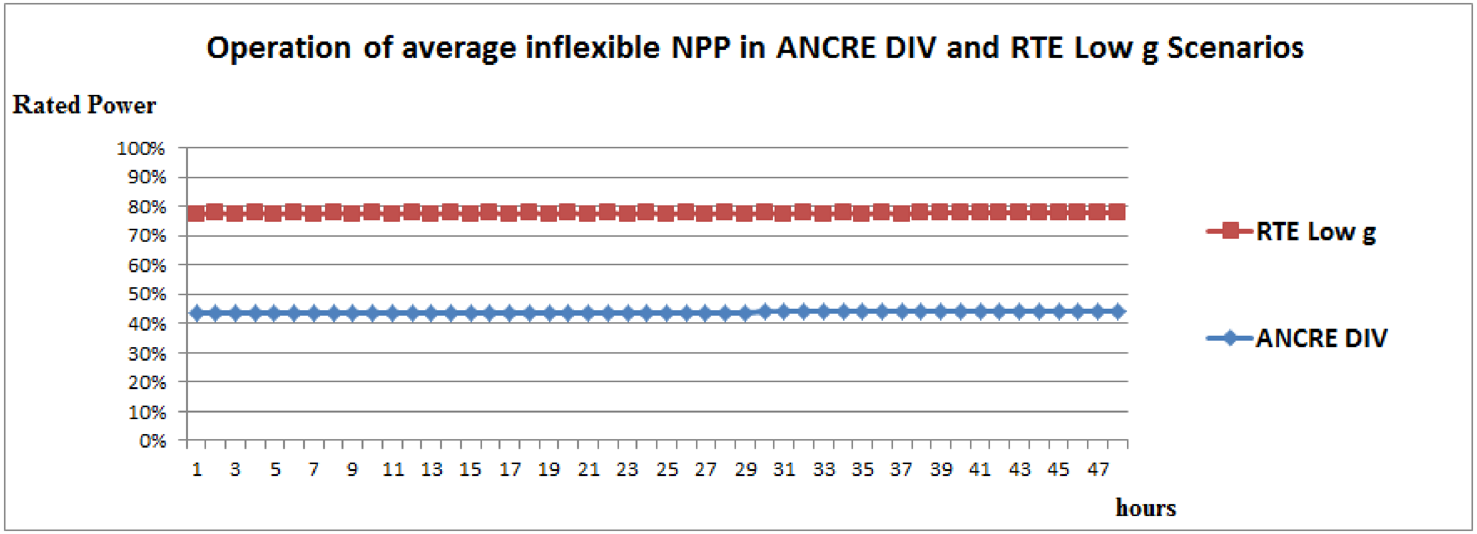
16 days reactor lifetime less.

Statistics of load-following operation of an average PWR reactor	# F0	# F1	# F2	# F3
Reactor design				
Cycle deepness	10%	20%	40%	60%
Annual budget of cycles, by fatigue type	1667	1667	250	200
Weight of each cycle type in the total fatigue	0.01%	0.03%	0.06%	0.08%
Model results, 2030				
Full cycles	**336**	**252**	**245**	**250**
Additional fatigue over one year by cycle type	0	0	0	4.13%
Reduced reactor lifetime, days, by cycle type	0	0	0	15
Reduced reactor total lifetime in 2030, days	**16**			

Load-following increases the load factor of flexible NPP.

- Inflexible NPP steady state operation is possible at only low load factors (Example: 68% over the year in Ancre DIV case).
- Load-following operation makes load factor increase (80% Ancre).

Reactor type	RTE Low g		RTE New mix		Ancre DIV	
	Load-follow	Reference	Load-follow	Reference	Load-follow	Reference
NPP flexible	76%	80%	73%	77%	80%	74%
NPP steady state	84%		81%		68%	



22

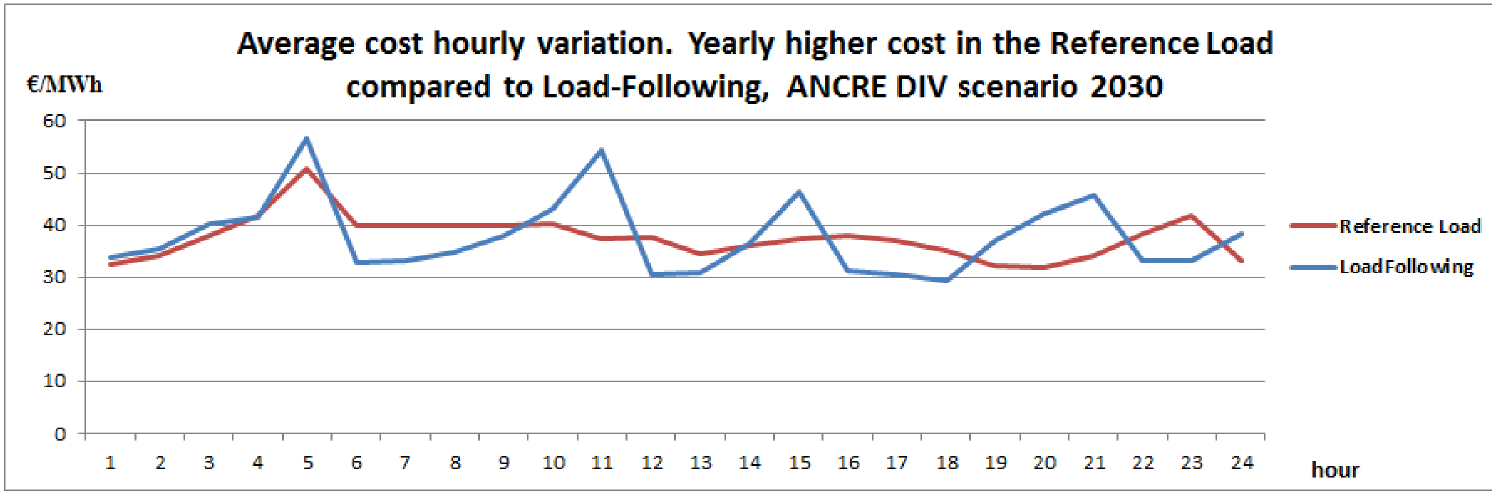
Results

Comparative Results LF versus Reference, ANCRE DIV scenario

Model OUTPUTS, France 2030, ANCRE DIV scenario					
	Load-Following		Reference Load		Load-follow - Reference
Technology	Generation	Annual Load	Generation	Annual Load	
	GWh	%	GWh	%	Δ
Nuclear	285 226	74%	285 226	74%	0
Coal	-	-	-	-	-
Hydro	61 454	35%	61 116	35%	338
Oil steam turbine	-	-	-	-	0
CCGT	3 633	3%	9 213	9%	-5 579
NGGT	179	0%	534	1%	-355
Biomass	40 559	46%	35 287	40%	5 272
CHP	9 636	10%	9 636	10%	0
Wind On-shore	46 616	18%	46 616	18%	0
Wind Off-shore	43 292	35%	43 292	35%	0
Solar	48 836	15%	48 726	15%	110
Other RES	-		-		-
Total Generation, GWh	539 430		539 645		-216
Storage provision, GWh	242		1161		919
Net Imports, GWh	-60 788		-60 788		0
CO_2 emissions, Mt	8.3		10.4		-2
Average Production Cost, €/MWh		35.0		35.2	-0.2
Average Marginal Price, €/MWh		95		95	0.6
System costs, M€		16 261		16 371	-110

23

When the NPP influence is large enough, power prices locally decrease .



Scenario	Consumer Power Price, €/MWh
	Variation, LF-REF, €/MWh
RTE Low g	-3.6
RTE New mix	0.0
Ancre DIV	-0.2

Shorter licence cycling budget of flexible reactors.

- Higher flexibility requirements for high IRES, high NUC, low Exports.
- Higher load factors, lower unit generation cost.
- But license exhausting could offset cost savings from higher load factors.

Comparison between Load-Following and Reference Load in 2030

Scenario	Reduced lifetime, days	Load Factor			LCOE, €/MWh		
	Load-Following	Load Following LF, %	Reference Load REF, %	**Variation LF-REF, hours**	Load Following LF, €/MWh	Reference REF, €/MW	**Variation LF-REF, €/MWh**
RTE Low g	7	76%	80%	**-367**	59.3	57.8	**1.5**
RTE New mix	15	73%	77%	**-385**	60.7	58.7	**2.0**
Ancre DIV	16	80%	74%	**551**	58.3	59.6	**-1.3**

High requirements for flexible NPP in scenarios with high shares of nuclear and IRES: ANCRE Div only

- **NPP:**
  - Costs are considered over the entire fleet, not separately for flex NPP.
  - Managing load-following involves all reactors, as all PWR flexi providers.
- **System effects:**
  - Not necessarily need of additional flexibility with NPP (Curtail = 0 in Reference).
  - System costs are lower: substitution of nuc with CHP, gas.
  - IRES do not replace nuclear power megawatt for megawatt.
  - Less CO2 emissions.

Comparison between Load-Following and Reference in 2030

Scenario	NPP operator revenues, €/MW			System Cost			CO2 emissions, Mt			IRES Curtailment		
	Load Following, LF, €/MW	Reference LF, REF, €/MW	**Variation, LF-REF, €/MW**	LF, M€/MW	REF M€/MW	**Variation LF-REF, €/MWnuc**	LF, Mt	REF Mt	**LF-REF Mt**	LF, MWh	REF, GWh	**LF-REF, GWh**
RTE Low g	1 258 833	1 260 279	**-1 446**	0.36	0.38	**-28 240**	24.1	30.7	**-6.6**	0	0	**0**
RTE New mix	1 232 118	1 232 118	**-0**	0.57	0.57	**0**	42.5	42.5	**0.0**	0	0	**0**
Ancre DIV	620 204	616 345	**3 859**	0.37	0.37	**-2 495**	8.3	10.4	**-2.2**	0	110	**-110**

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Win-win situation is obtained in Ancre scenario, where all stakeholders record gains from NPP operating flexibly.

- Ensuring flexibility with nuclear power becomes an interesting case for nuclear power operators if they can influence the market price or the equilibrium volume to can record more revenues.

Gains from flexible nuclear power, by stakeholder

Scenario	Stakeholder			
	NPP	Consumer	System	IRES operator
RTE Low g	-	++	++	0
RTE New mix	-0	0	0	0
Ancre DIV	+	+	+	+

Regulatory insights

- **NPP operators**
  - **What options for a NPP operator to operate load-following or baseload?**
  - **What room of manœuvre for market price speculation?**
  - **Need to compensate for the missing money.**

- **Decision-makers**

Public Choice criteria based on hourly NUC-IRES interaction:

  - Asset use (Load Factor): efficiency rate
  - System costs
  - Pareto-optimality / win-win situation

Final remarks

- Regulation requirements
  - Market context: low spot prices and high price volatility.
  - Measure: Integrating flexibility costs (where positive) into spot market prices.
  - Regulatory measures in complement to spot market contracts to guarantee the recovery of investment costs.
    - Capacity market – it complements the wholesale market to can cover the fixed costs
    - Contracts for differences – the nuclear operator is paid for the missing money
    - Financial Transmission Rights – hedge against reduced LF due to congestion.
- Technical requirements to provide flexibility
  - A new reactors design would avoid O&M ramping costs + depreciation.

Take away message
If better equilibrium when redistributing the surplus created, then need of policy and regulatory measures to share the rent created with the nuclear power flexibility.

Thank you for your attention!

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The less attractive environment is met in systems with large baseload capacities: high load-following needs, excessive NPP cycling, shorter technical lifetime.

Good economic environment is obtained for the following combinations:

- medium interconnectivity – flexible systems – medium RES share – no overgeneration;
- low interconnectivity – large RES shares – large NUC shares;
- medium interconnectivity – no overgeneration – medium to high RES.

LF RTE g	LF RTE mix	LF Ancre
more hydro	more nuc	more hydro
less CHP	less CHP	less gas
more storage	less storage	more biomass
less exports	more exports	more pv
		less storage