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Nuclear generation and flexibility modeling in renewables-driven electric systems :

Arthur LYNCH, Sophie GABRIEL

03/30/2021

Context :

Variable Renewable Energies (VRE) are expected to answer most of the future electric demand

The integration of a large share of VRE will increase the flexibility required to meet the demand-supply equilibrium

This creates a new paradigm where the flexibility of nuclear will be determining its role

How can we model a flexible nuclear fleet to determine its future role in renewables-driven electric systems ?

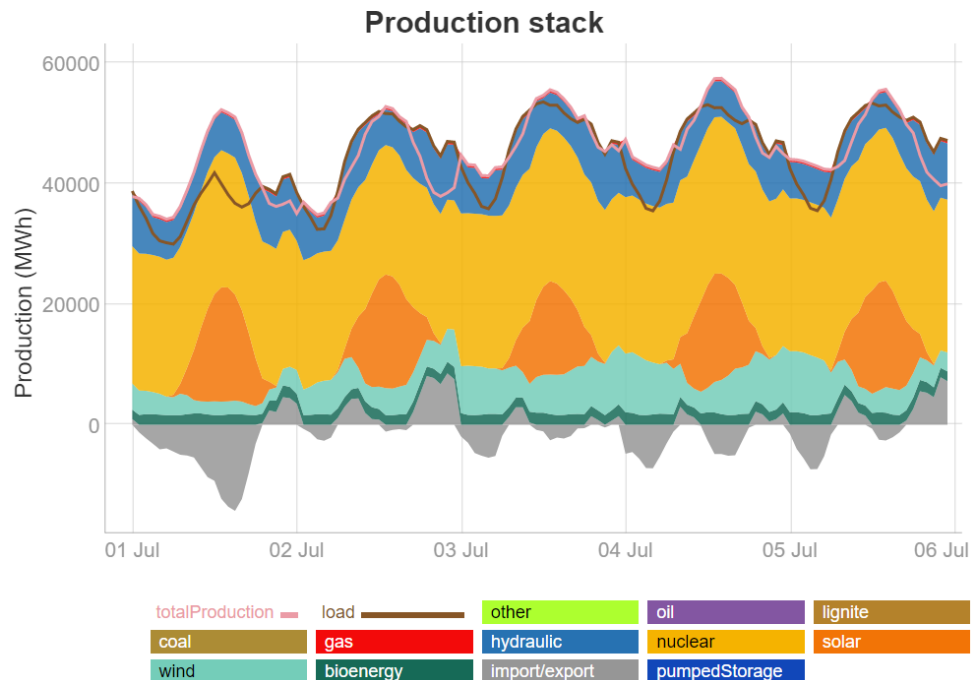


Context :

In order to determine the role of each generating technology in future electric systems, the literature uses economic dispatch simulation/capacity expansion models

Ex : GenX (MIT), Antares Simulator (RTE), EOLES (CIRED), PyPSA (KIT)...

They aim to foresee the economically optimal mix, considering technologies' costs, carbon footprint, and technical constraints.



Output example of Antares Simulator (RTE) : Weekly economic dispatch between technologies

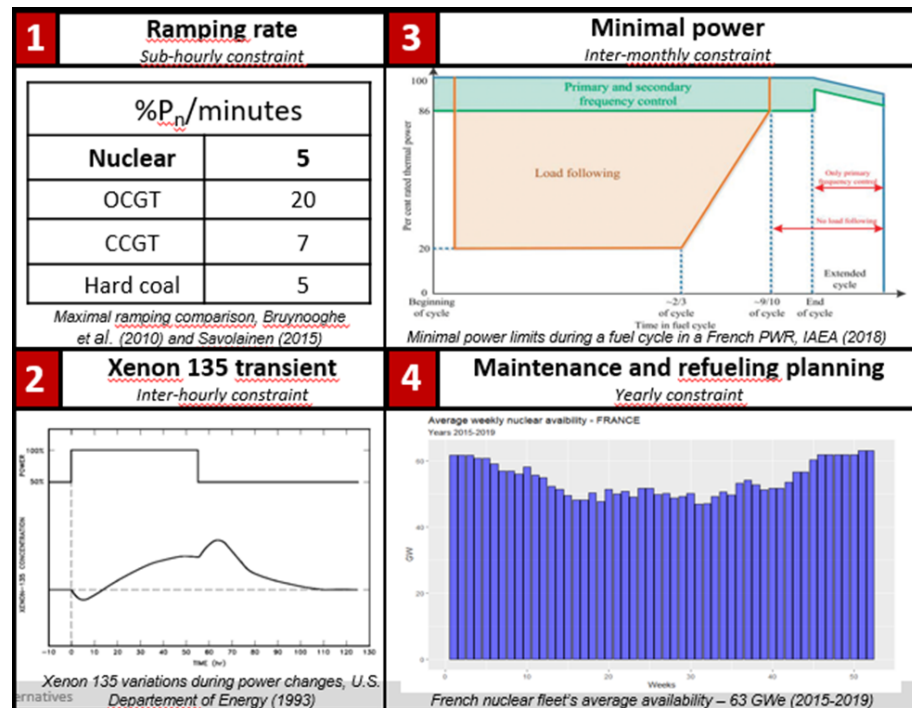
What are nuclear flexibility technical constraints ? How are those constraints modeled in the literature ?

Nuclear flexibility modelling practices : vs. Physics-induced approach :

- 1) Hourly ramping rates:
Ex : 25% P_n/h

- 2) Constant minimal power :
40/50% P_n

- 3) Constant nuclear availability throughout a year :
 $Nuclear\ availability = Installed\ capacity \times Average\ availability\ factor$



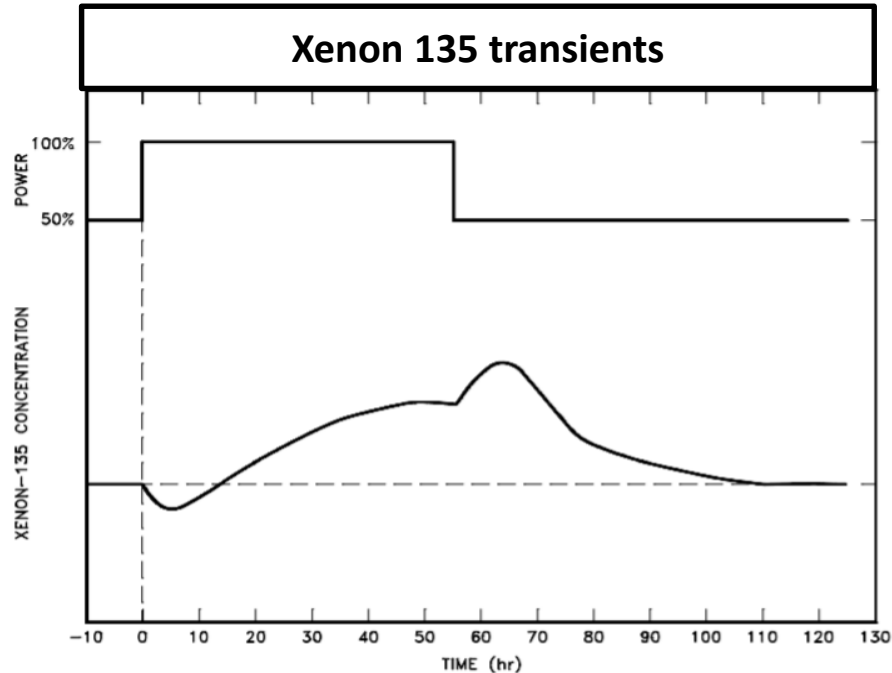
Physics-induced approach : Sub-hourly :

Ramping rates	
%P _n /minutes	
Nuclear	2-5
OCGT	20
CCGT	7
Hard coal	5

Maximal ramping comparison, Bruynooghe et al. (2010) and Savolainen (2015)

Ramping rates prevent the reactors' maneuvering speed at a sub-hourly scale but not at an hourly scale

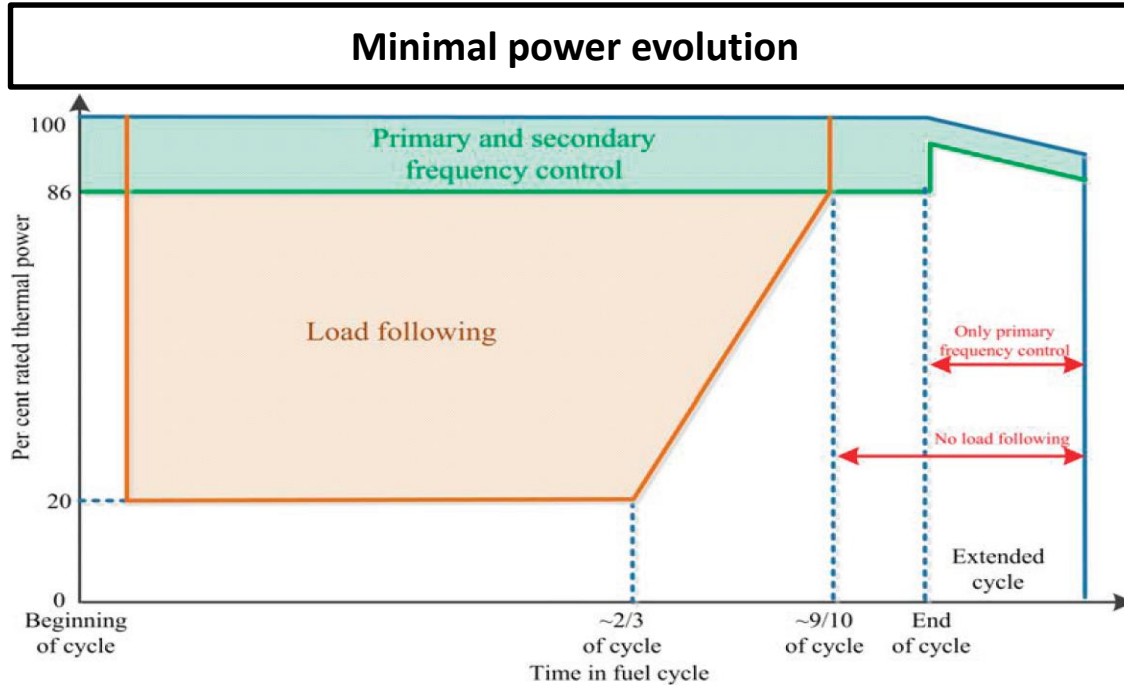
Physics-induced approach : Inter-hourly :



*Xenon 135 variations during power changes, U.S.
Department of Energy (1993)*

Xenon 135 transients prevent reactors
from successively maneuvering

Physics-induced approach : Inter-monthly :



Minimal power limits during a fuel cycle in a French PWR, IAEA (2018)

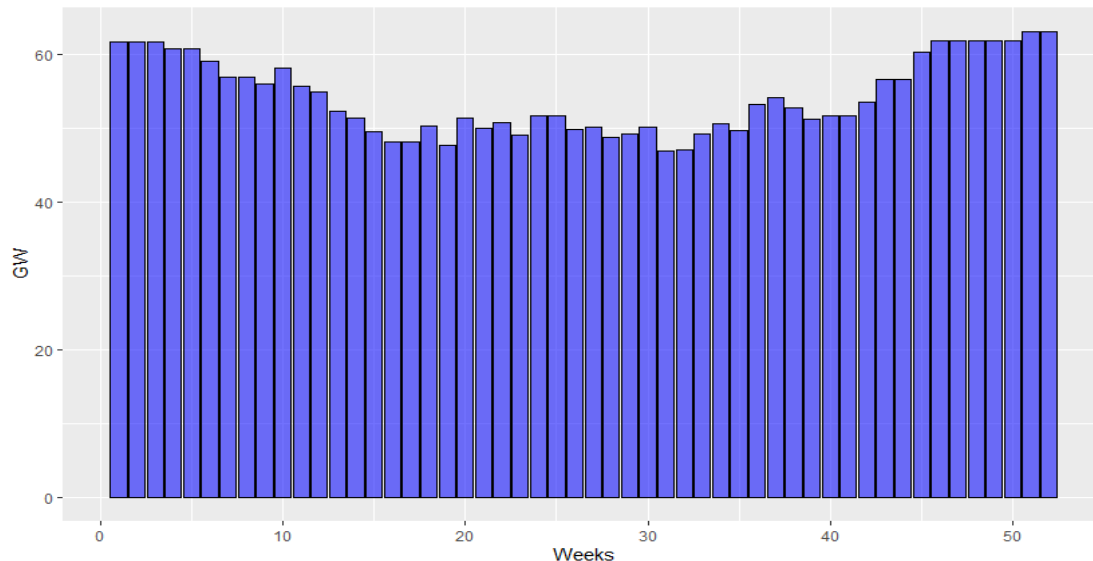
The reactors' load-following capabilities evolve throughout their fuel's irradiation cycle. After 90% of this cycle, load-following capabilities are null.

Physics-induced approach : Inter-annual :

Maintenance and refueling planning

Average weekly nuclear availability - FRANCE

Years 2015-2019



French nuclear fleet's average availability – 63 GWe (2015-2019)

The fleet's available generation and flexibility is variable throughout the year

Three constraints seem determinant to the behavior of nuclear PWR in current economic dispatch models :

- 1) Inter-hourly: Xenon 135 transients
- 2) Inter-monthly : Minimal power evolution
- 3) Inter-annual : Operational planning

As most models have an hourly timestep, sub-hourly ramping rates constraints may not influence the reactors' behavior

The relevance of Xenon 135 transients and minimal power evolution constraints to model nuclear flexibility has been assessed in :

- J. Jenkins et al., "The benefits of nuclear flexibility in power system operations with renewable energy" Appl. Energy, vol. 222, pp. 872–884, Jul. 2018, doi:10.1016/j.apenergy.2018.03.002
- R. Ponciroli et al., "Profitability Evaluation of Load-Following Nuclear Units with Physics-Induced Operational Constraints" Nucl. Technol., vol. 200, no. 3, pp. 189–207, Dec. 2017, doi: 10.1080/00295450.2017.1388668.

Case study : Is the operational planning relevant to nuclear modeling in renewables-driven electric systems ?

Method :

Comparison of two simulation cases :

Optimized nuclear planning

Vs :

Average nuclear availability

Of a simplified electric system :

One country modeled – France – 6 cases

471.2 TWh
demand level
(entso-e)

VRE penetration
scenarii :

- 20 GW Solar, 20 GW Wind
- 30 GW Solar, 45 GW Wind
- 40 GW Solar, 70 GW Wind

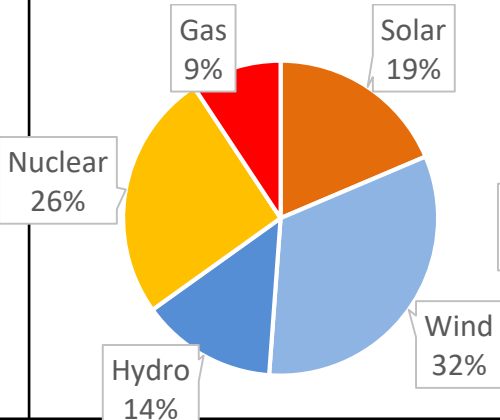
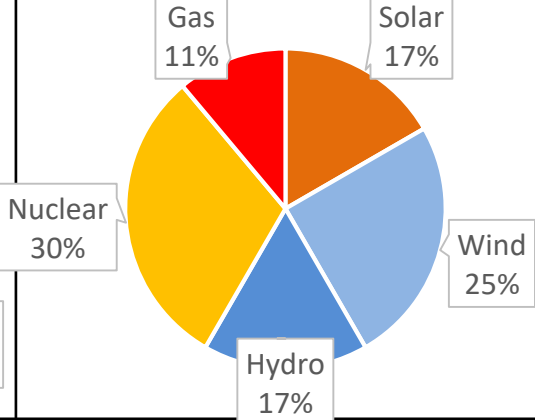
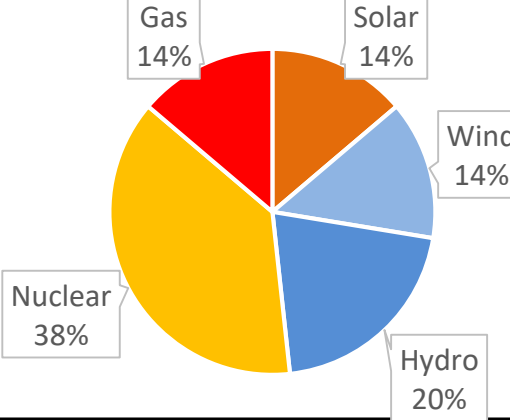
Other capacities :
55 GW Nuclear
5 GW Gas
30 GW Hydro

No network constraints

Technologies costs
based on [\[1\]](#)

[\[1\]](#) French data, Projected costs of generating electricity, France, 2020 Edition, NEA-OECD, 2020

Capacity mix for each scenario

Scenario name	Renewables 66% Based on the prospective scenario N3 - RTE	Renewables 50%	Renewables 33%																																				
Installed renewables capacity	40 GW Solar 70 GW Wind Total capacity : 200 GW	30 GW Solar 45 GW Wind Total capacity : 165 GW	20 GW Solar 20 GW Wind Total capacity : 130 GW																																				
Capacity mix	 <table border="1"> <thead> <tr> <th>Source</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Nuclear</td> <td>26%</td> </tr> <tr> <td>Wind</td> <td>32%</td> </tr> <tr> <td>Hydro</td> <td>14%</td> </tr> <tr> <td>Gas</td> <td>9%</td> </tr> <tr> <td>Solar</td> <td>19%</td> </tr> </tbody> </table>	Source	Percentage	Nuclear	26%	Wind	32%	Hydro	14%	Gas	9%	Solar	19%	 <table border="1"> <thead> <tr> <th>Source</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Nuclear</td> <td>30%</td> </tr> <tr> <td>Wind</td> <td>25%</td> </tr> <tr> <td>Hydro</td> <td>17%</td> </tr> <tr> <td>Gas</td> <td>11%</td> </tr> <tr> <td>Solar</td> <td>17%</td> </tr> </tbody> </table>	Source	Percentage	Nuclear	30%	Wind	25%	Hydro	17%	Gas	11%	Solar	17%	 <table border="1"> <thead> <tr> <th>Source</th> <th>Percentage</th> </tr> </thead> <tbody> <tr> <td>Nuclear</td> <td>38%</td> </tr> <tr> <td>Wind</td> <td>14%</td> </tr> <tr> <td>Hydro</td> <td>20%</td> </tr> <tr> <td>Gas</td> <td>14%</td> </tr> <tr> <td>Solar</td> <td>14%</td> </tr> </tbody> </table>	Source	Percentage	Nuclear	38%	Wind	14%	Hydro	20%	Gas	14%	Solar	14%
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Operational planning unit-commitment program:

Objective function :

$$\text{Maximize } \sum_{t=1}^T \sum_{i=1}^N e^{\text{ResidualDemand}_t} * P_{\text{nom}_i} * U_{it}$$

*Constrained by :**Irradiation cycle length constraints:*

$$(1) \quad \forall x \in [0; \text{MinimumOn}_i] : U_{i,t+x} \geq U_{i,t} - U_{i,t-1}$$

$$(2) \quad \sum_{x=0}^{x=\text{MaximumOn}_i} U_{i,t+x} \leq \text{MaximumOn}_i$$

Maintenance and refueling length constraints:

$$(3) \quad \forall x \in [0; \text{MinimumOff}_i] : U_{i,t+x} \leq 1 + U_{i,t} - U_{i,t-1}$$

$$(4) \quad \sum_{x=0}^{x=\text{MaximumOff}_i+1} U_{i,t+x} \geq 0$$

Reactor	Nominal power (MW)	Minimum stable power (MW)	Cycle-length (days at full power)
Nogent_1	1310	655	395
Nogent_2	1310	655	395
Penly_1	1330	665	395
Penly_2	1330	665	395
Golfech_1	1310	655	395
Golfech_2	1310	655	395
ChoozB_1	1500	750	380
ChoozB_2	1500	750	380
Civaux_1	1494	747	380
Civaux_2	1494	747	380
Flamanville_3	1570	785	380
25 * EPR2	1600	800	400

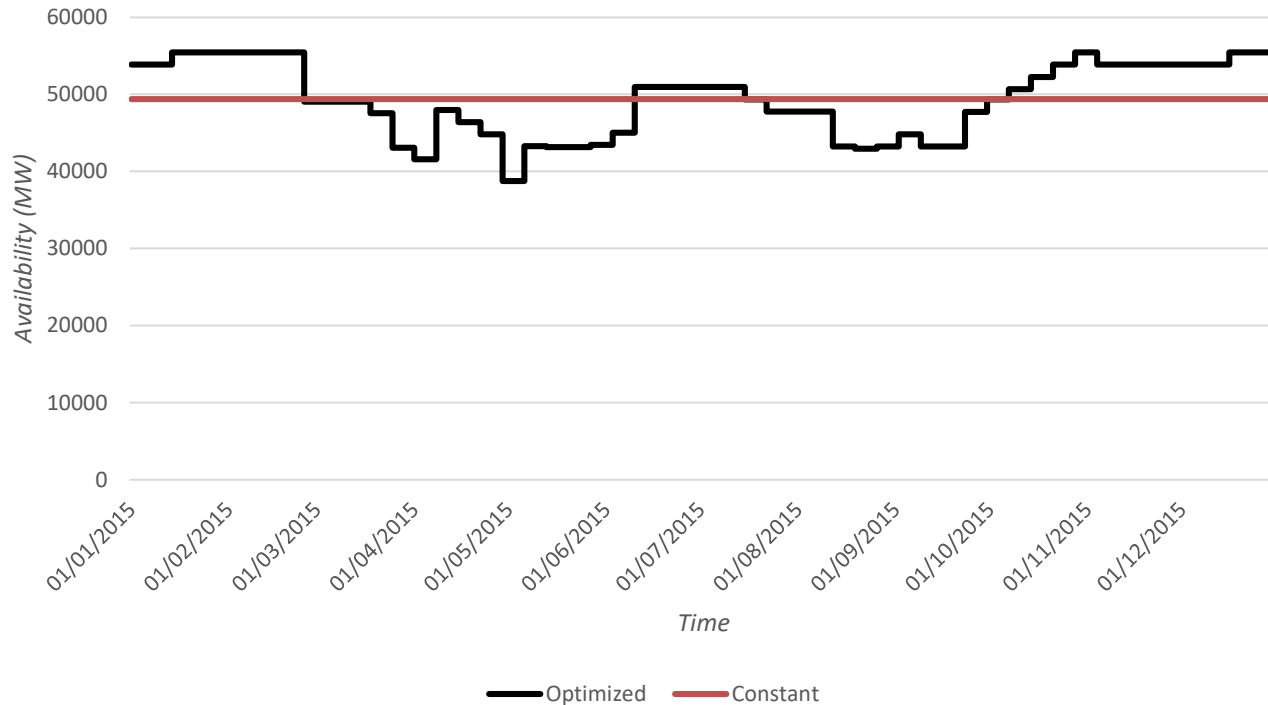
where : T : number of week of optimization N : number of reactors ResidualDemand_i : Level of the residual demand, week t P_{nom_i} : Nominal power of reactor i

$$U_{it} : \begin{cases} 1 & \text{if reactor } i \text{ is available at time } t \\ 0 & \text{if reactor } i \text{ is closed at time } t \end{cases}$$

 MinimumOn_i : Minimum functioning time of reactor i MinimumOff_i : Minimum maintenance /refueling time of reactor i MaximumOn_i : Maximum functioning time of reactor i MaximumOff_i : Maximum maintenance /refueling time of reactor i

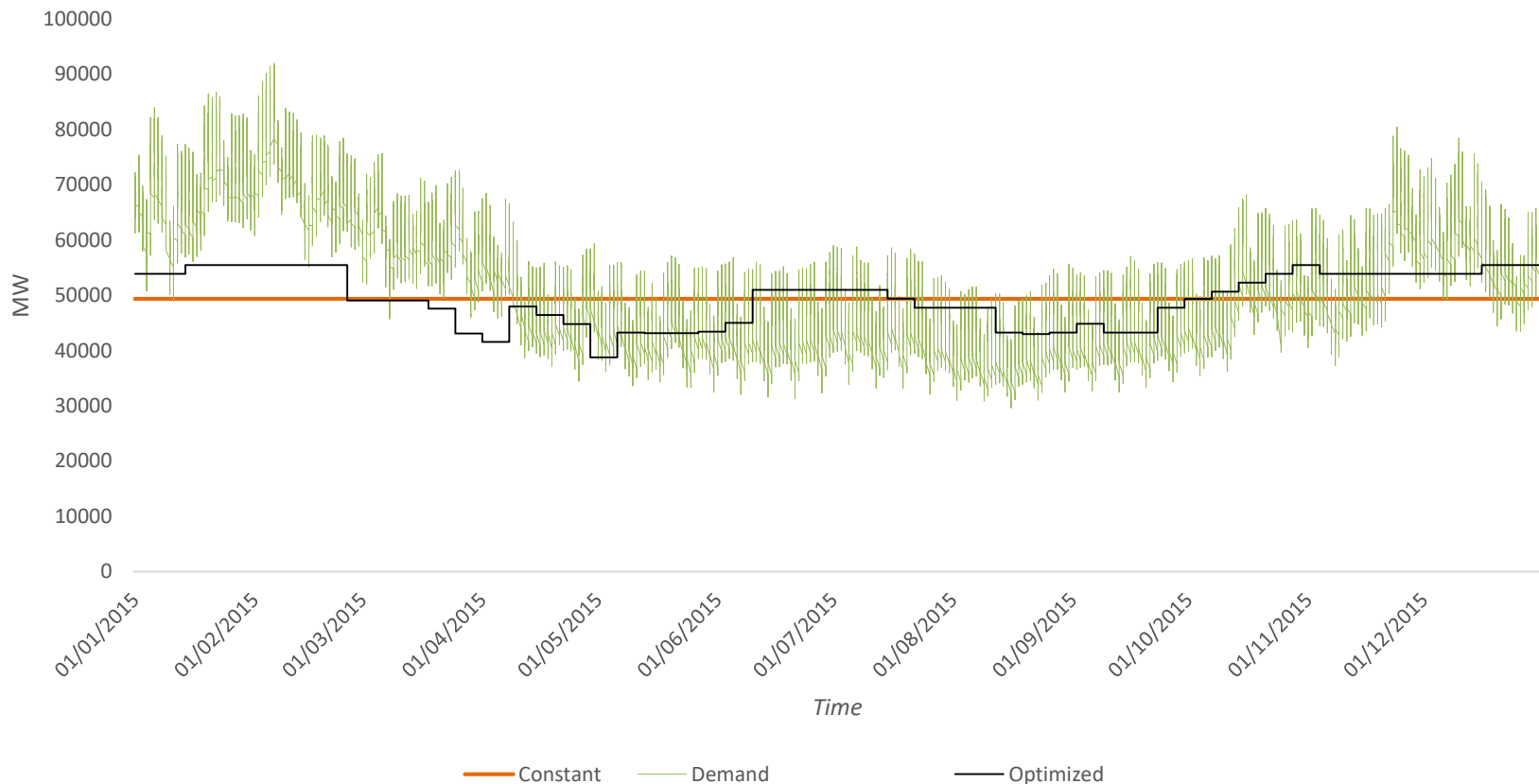
Resulting optimized nuclear planning: 55 GW nuclear capacity

Nuclear availability - Year



Average
capacity factor :
89%

Nuclear availability vs. Demand



Economic Unit-Commitment Dispatch model using ANTARES-Simulator (RTE):

Objective function :

$$\text{Minimize } \sum_{s=1}^{52} \sum_{t=1}^{7*24} \sum_{i=1}^N p_i * Q_{i,t,s} * U_{i,t,s}$$

*Constrained by :**Demand – Supply Equilibrium constraint :*

$$(1) \quad \sum_{i=1}^N Q_{i,t,s} * U_{i,t,s} \geq \text{Demand}_{t,s}$$

Maximum and minimum production level :

$$(2) \quad Q_{i,t,s} \leq \overline{Q_{i,t,s}} * U_{i,t,s}$$

$$(3) \quad Q_{i,t,s} \geq \underline{Q_{i,t,s}} * U_{i,t,s}$$

Minimum Up and Downtime :

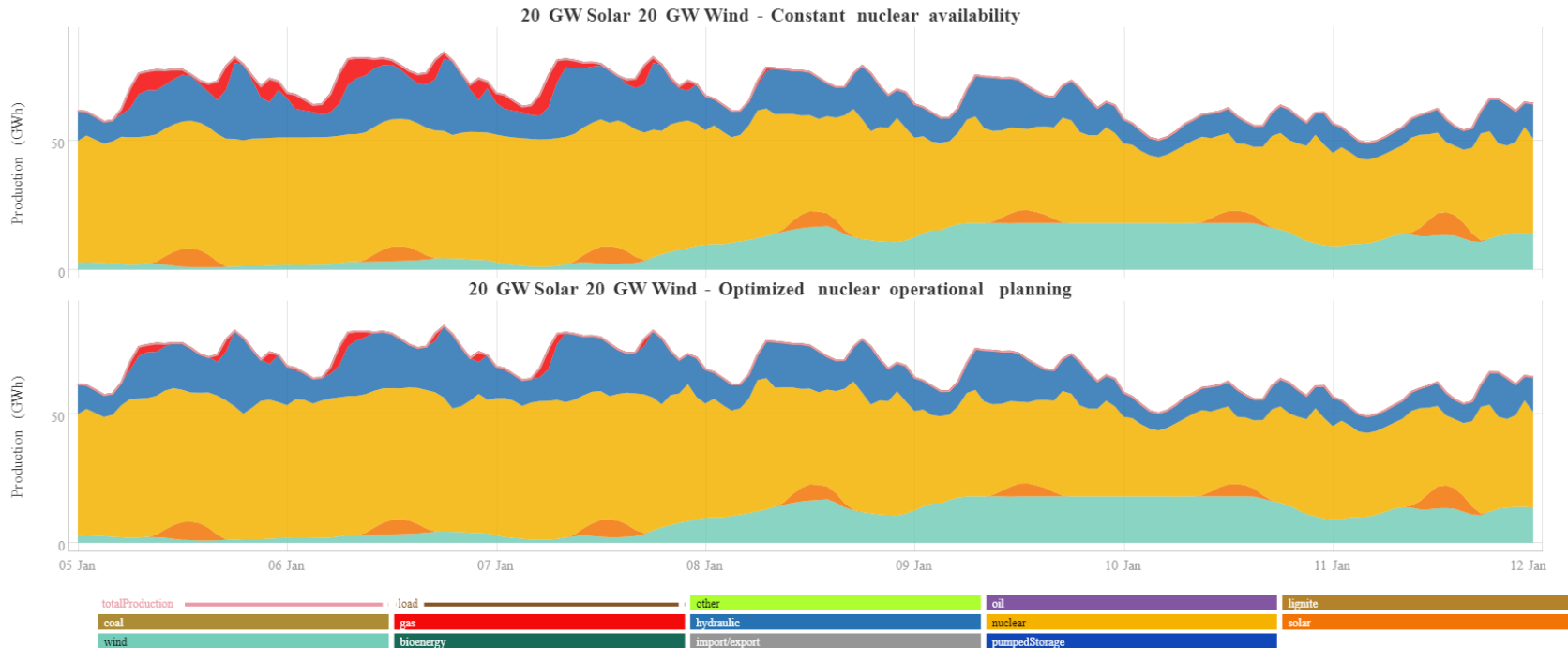
$$(4) \quad \forall x \in [0; \text{MinimumUp}_i] : U_{i,t+x,s} \geq U_{i,t,s} - U_{i,t-1,s}$$

$$(5) \quad \forall x \in [0; \text{MinimumDown}_i] : U_{i,t+x,s} \leq 1 + U_{i,t,s} - U_{i,t-1,s}$$

*where :**N: number of generating plants**p_i: marginal cost of generating plant i**Q_{i,s,t}: generation of plant i at time t in week s*

$$U_{i,s,t}: \text{binary variable} \begin{cases} 1 & \text{if plant } i \text{ is up at time } t \text{ in week } s \\ 0 & \text{if plant } i \text{ is down at time } t \text{ in week } s \end{cases}$$
 $\overline{Q_{i,t,s}}$ *: Maximum production capacity of plant i at time t of week s* $\underline{Q_{i,t,s}}$ *: Minimum production capacity of plant i at time t of week s**MinimumUp_i**: minimum number of hours plant i has to operate before shutting down**MinimumDown_i**: minimum number of hours plant i has to shut down before re – starting*

Case study : Simulation dispatch – Output examples



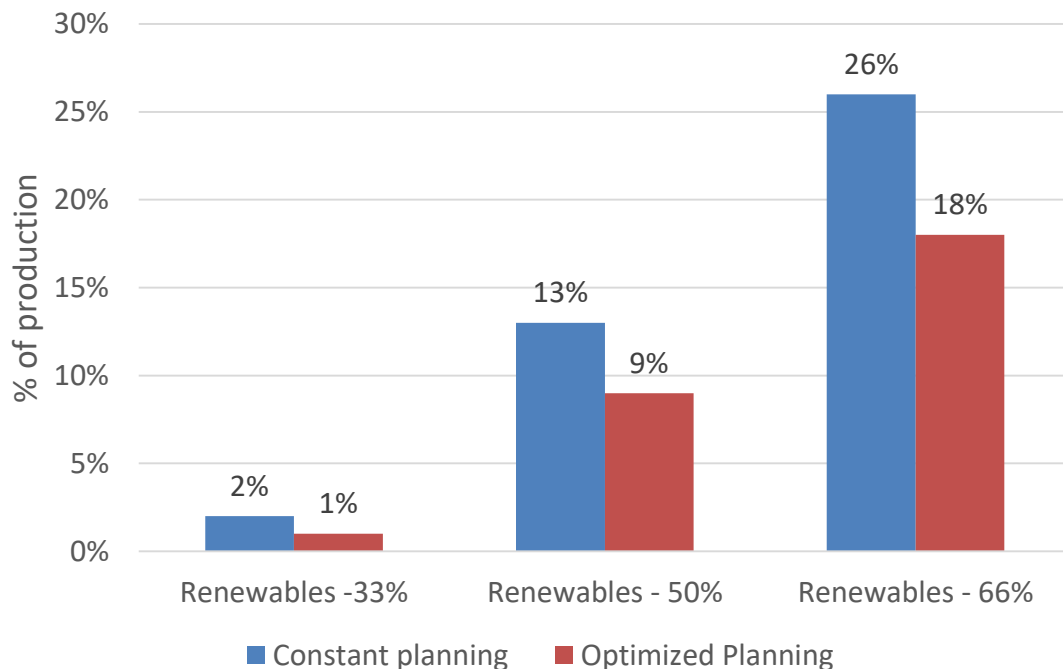
Hourly economic dispatch – January 05-12 – Year 2015

Case study : Simulation dispatch – Annual results

Simulation	Renewables 66%		Renewables 50%		Renewables 33%	
	Constant	Optimized	Constant	Optimized	Constant	Optimized
Demand (TWh)	471,2					
Solar (TWh)	52,5		39,4		26,3	
Wind (TWh)	183		117,8		52,3	
Hydro (TWh)	102,1					
Nuclear (TWh)	204	184	245,4	234	293,5	292,8
Gas (TWh)	0	0	0,78	0,19	2,27	0,69
Spilled (TWh)	70,5	50,3	33,8	21,8	4,8	2,5

Annual production level of each technologies for each scenario– Year 2015

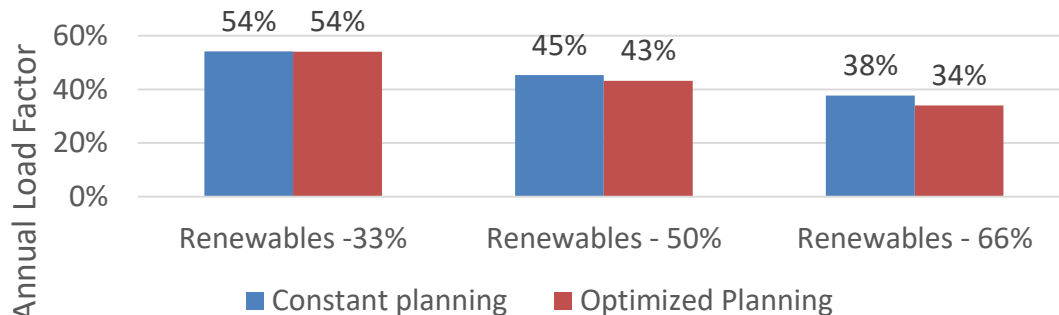
Case study : Simulation dispatch – Annual results

Spilled nuclear energyComments :

The level of spilled nuclear production is higher as the fleet's availability is constant throughout the year.

The gap between the two nuclear availability cases increases as VRE penetration in the capacity mix increases.

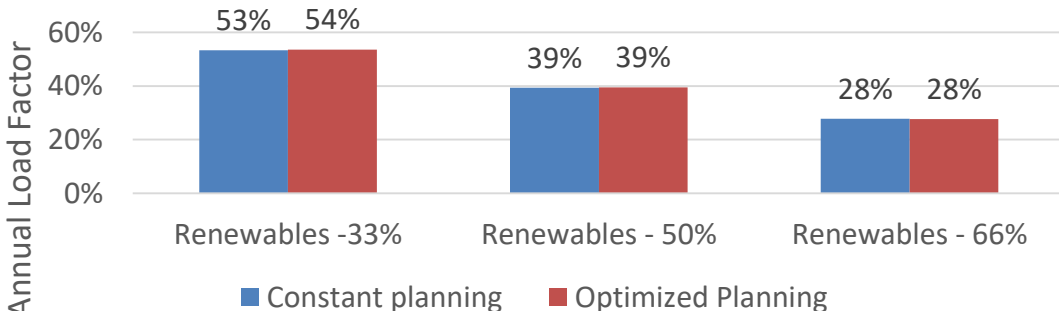
Case study : Simulation dispatch – Annual results

Nuclear load factorComments :

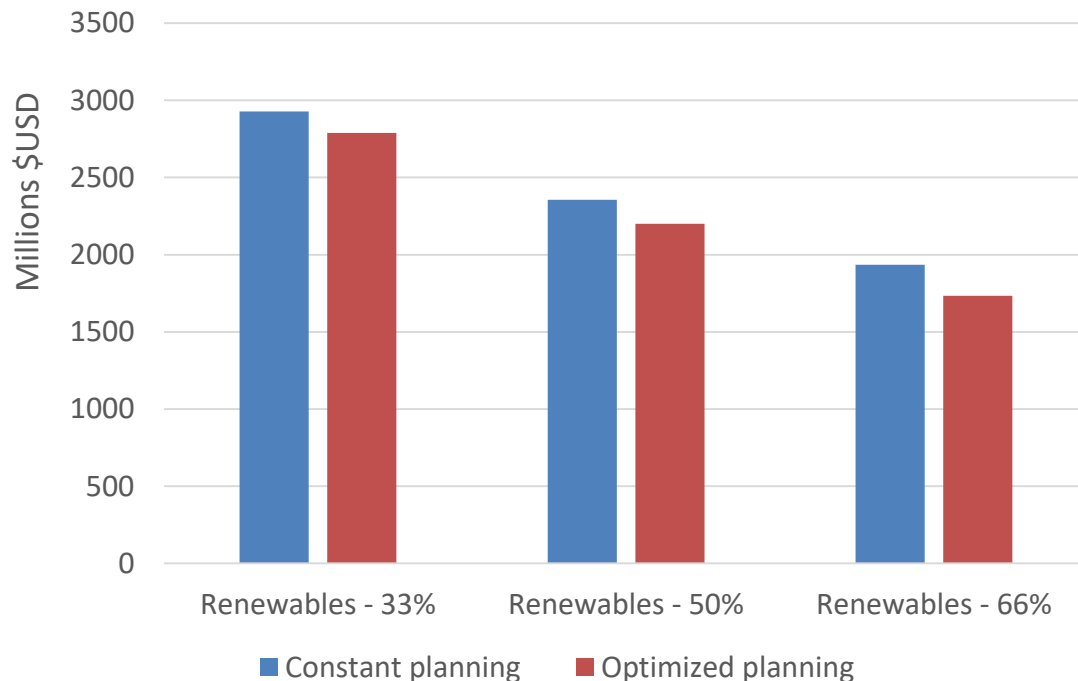
Nuclear production level is higher as the fleet's availability is constant throughout the year. However, this implies higher levels of nuclear spilled energy.

When accounting for the spilled nuclear production, the production levels are similar.

Note: The low load factors are due to the pro-eminent share of nuclear in the capacity mix

Nuclear load factor (minus spilled energy)

Case study : Simulation dispatch – Annual results

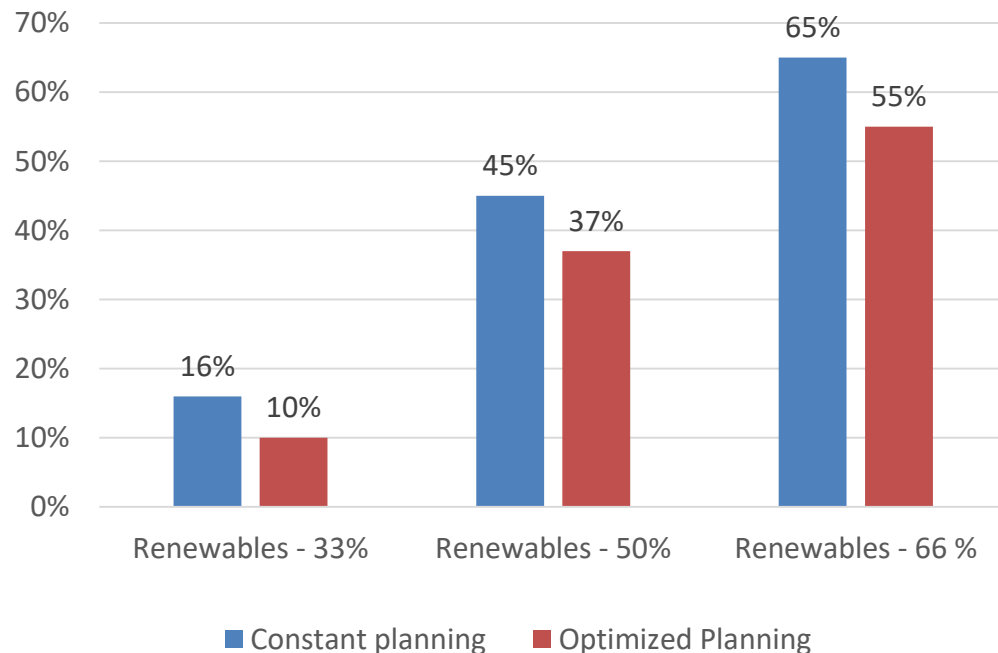
Operational cost of the systemComments :

The annual operational cost decreases as the fleet's operational planning is optimized.

The gap between the two nuclear availability cases increases as VRE penetration in the capacity mix increases.

Note: The operational cost does not account for fixed, investment and network costs

Case study : Simulation dispatch – Annual results

Share of negatives pricesComments :

As there are few technologies modeled, most of them with null marginal costs, the occurrence of negative prices is greater than reality.

Optimizing the operational nuclear planning seems to decrease the occurrence of negative prices, thus improving the economic viability of nuclear reactors.



Case study : Preliminary results

Modeling the optimized nuclear operational planning seems to be of greater interest as the flexibility required to the nuclear fleet increase (i.e. as the share of VRE heightens).

The main results associated with the optimization of the nuclear operational planning are :

- A cut in the overall spilled energy of the system, minimizing the system's operational costs
- A diminished use of peaking plants to ensure the supply-demand equilibrium
- An increased average market price due to a decreasing occurrence of spilled energy and negative prices

Further cases should be explored to assess the stakes surrounding the fleet's operational planning optimization to assess its future role in renewables-driven electric systems



Thanks for your attention