# *PLANNING CAPACITY INVESTMENTS AND FLEXIBILITY ASSETS:*

## *AN INVESTMENT MODEL INTEGRATING THE SHORT-TERM REQUIREMENTS WITH THE LONG-RUN DYNAMICS*

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CHAIRE EUROPEAN ELECTRICITY MARKETS
Fondation Paris-Dauphine

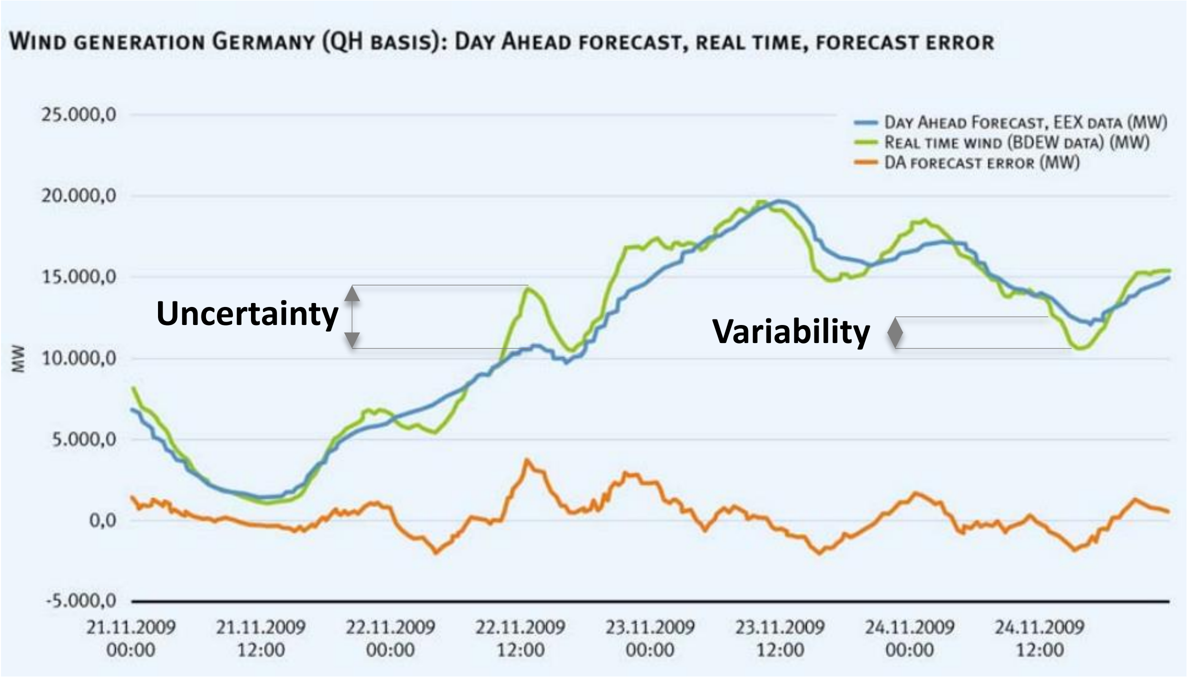
# 1. The power system in context

**The impact of increasing shares of I-RES on power systems and electricity markets:**

Amplified uncertainty and variability of net load in the short-term

Short-term (sec-min)

- **Balancing:** augmented need for non-event operating reserve (Power control and load following): *Need for improved forecast*
- **Higher need for other ancillary services:** *need for enhanced BRP*
- **Congestion management:** *LMP, market splitting, market coupling*.




**Source: EURELECTRIC, 2010**

# 1. The power system in context

**The impact of increasing shares of I-RES on power systems and electricity markets:**

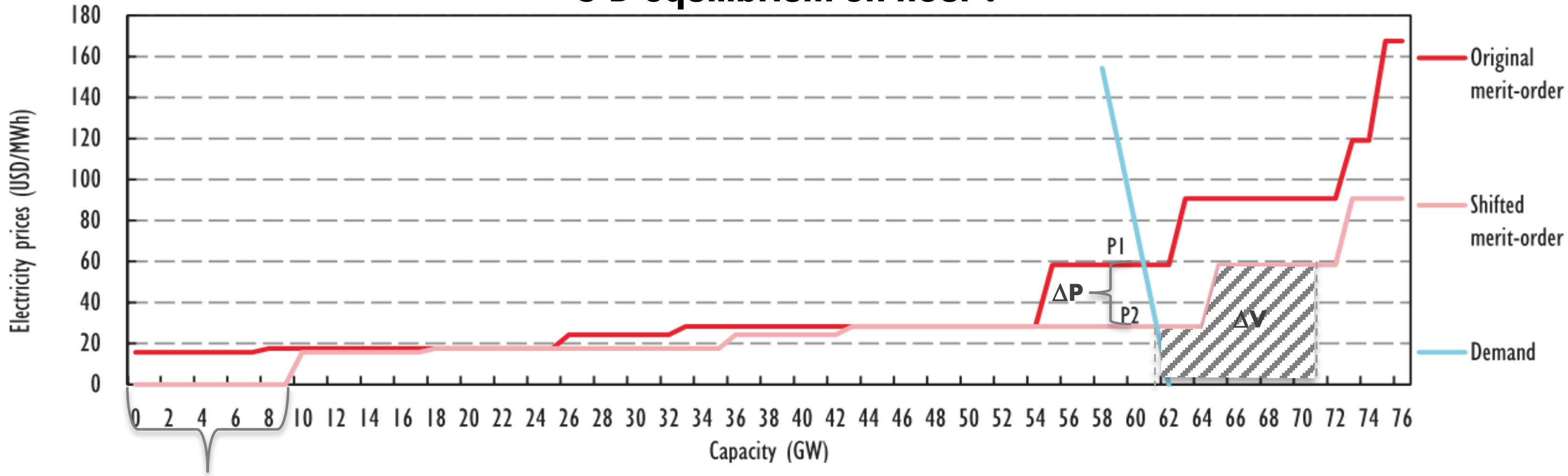
Low short-run marginal cost I-RES enter first in the merit order

Mid-term

(h)

- **Merit Order Effect:** reduced volumes and prices => reduced revenues
- **There are more constringent ramping restrictions binding the dispatch, but there is a higher need for availability and flexibility.** *Capacity mechanisms.*

**S-D equilibrium on hour *t***




**Source: IEA, 2014**

10GW of peaking units → Exceeding offers on the balancing market

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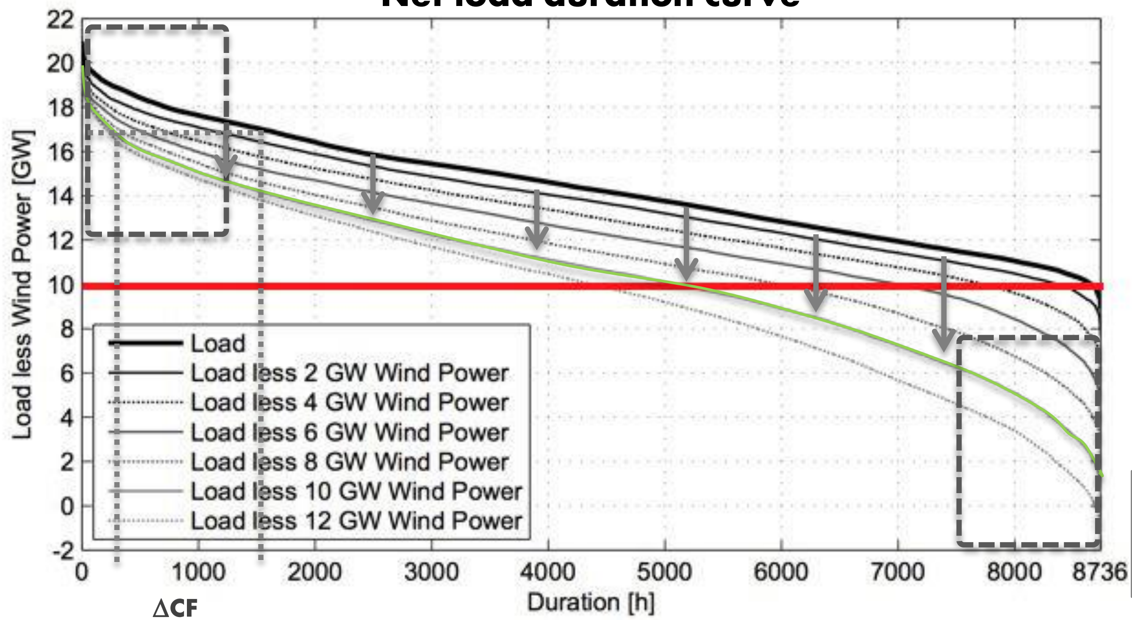
- **There are more constringent ramping restrictions binding the dispatch, but there is a higher need for flexibility**
- **Additional cost are incurred due to load following, wear and tear costs and part load efficiencies** => <u>higher operational cost of individual units</u>
- **Net load duration curve decreases and becomes stepper** => <u>missing money problem</u> *("Missing money or missing markets", Newbery 2015)*

**Net load duration curve**




Exceeding offers on the balancing market

# 1. The power system in context

**The impact of increasing shares of I-RES on power systems and electricity markets:**

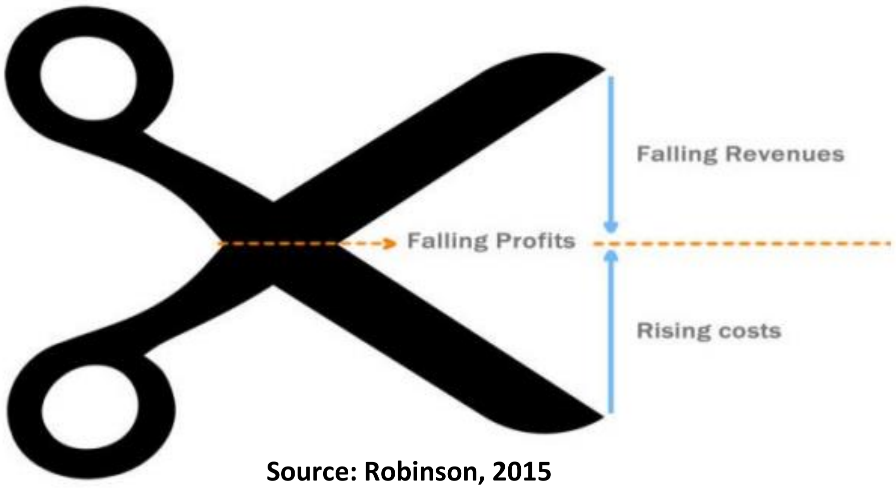
Depreciated profits: peaking plants mothballing and no investment incentives

Long-term

(years)

- **Cumulated losses of profits causes a SCISSOR EFFECT in the long-run**

  => Retirement of peaking plants. E.x: *Mothballing of 20GW CCGT capacity from EU markets of which 8,8GW were "recently" installed units*
- **Capacity adequacy problems**: depreciated prices cause no inframarginal rent threatening incentives for new investments.
- **Energy security issues:** not enough capacity when needed => blackout risk




**Source: Robinson, 2015**

# 1. The power system in context



## System dependent and interrelated issues

**Long-term (years)**

- **Scissor effect**
- **Capacity adequacy problems** (scissor effect)
- **Energy security issues**

**Mid-term (h)**

- **Merit Order Effect**
- **Less flexible dispatch but higher flexibility is needed**
- **Higher operational cost for committed units**
- **Missing money problem**

**Short-term (sec-min)**

- **Increased need for ancillary services**
- **Balancing issues**
- **Congestion management**

# 1. The power system in context



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# 1. The power system in context



**Flexibility (mid-term)**

- « Peak Shaving » (Intraday)
- I-RES integration
- Weekday/weekend arbitrage

**Multiple services**

**Adequacy**

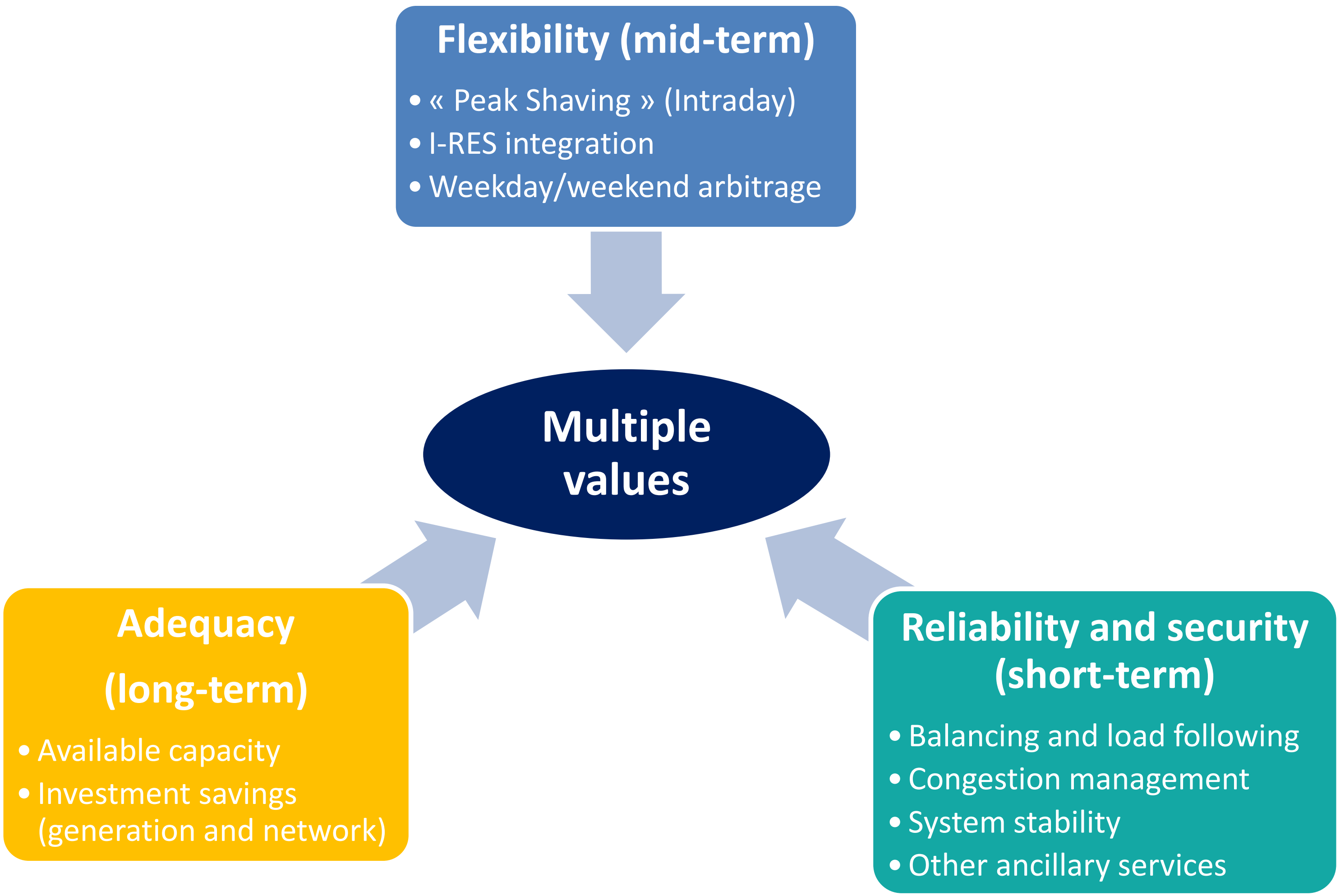
**(long-term)**

- Available capacity
- Investment savings (generation and network)

**Reliability and security (short-term)**

- Balancing and load following
- Congestion management
- System stability
- Other ancillary services

# 1. The power system in context




The cheapest technologies might not necessarily deliver the greatest value

# 2. Research questions

*A benchmark for a "market design 2.0":*

***What would be the power system that minimizes total cost and guarantee operability and reliability requirements?***

- **Do operability and reliability matter while planning capacity investment?**
  - To what extent are them relevant?
  - What are the most meaningful among them?

- **What is the real value of generation technologies (Conventionals, I-RES)?**
  - Is that value dependent on the power system representation adopted?

- **Should flexibility investment options be considered on the power system of the future?**
  - What is the role of electric storage technologies and DSM capabilities?
  - Are them in competition?

# 2. Research questions

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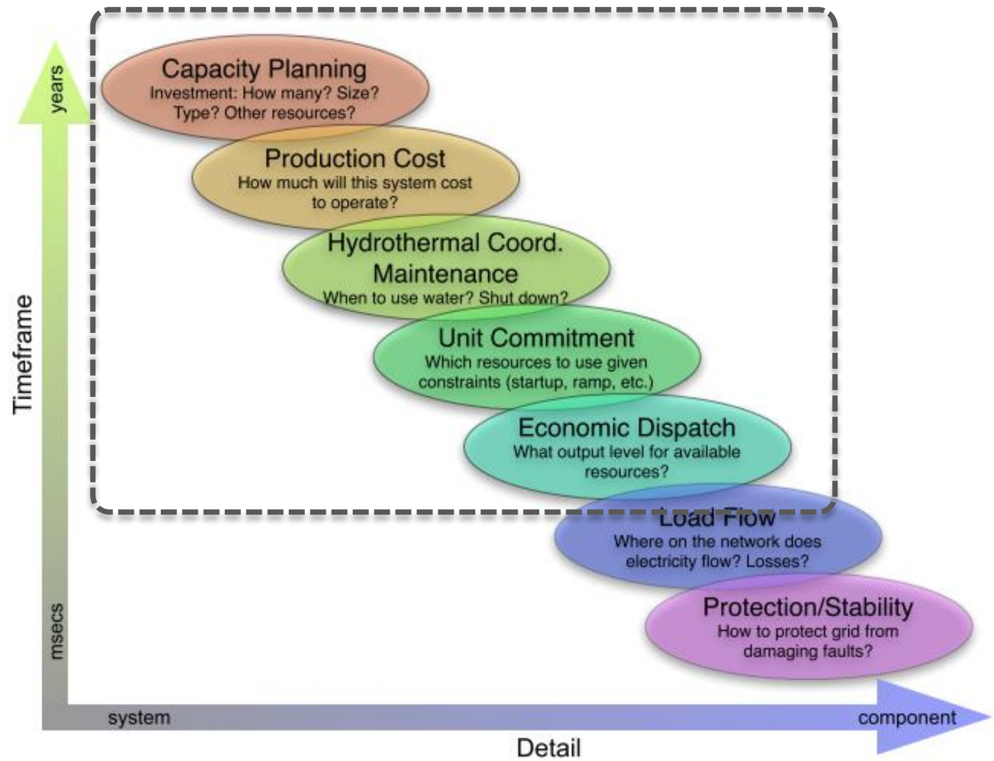
***Designing  the power systems:*** *linking timeframes with system requirements*




**Source: B. Palmintier, "Incorporating operational flexibility into electricity generation planning - Impacts and methods for system design and policy analysis," MIT, 2013**

# 3. Methodology

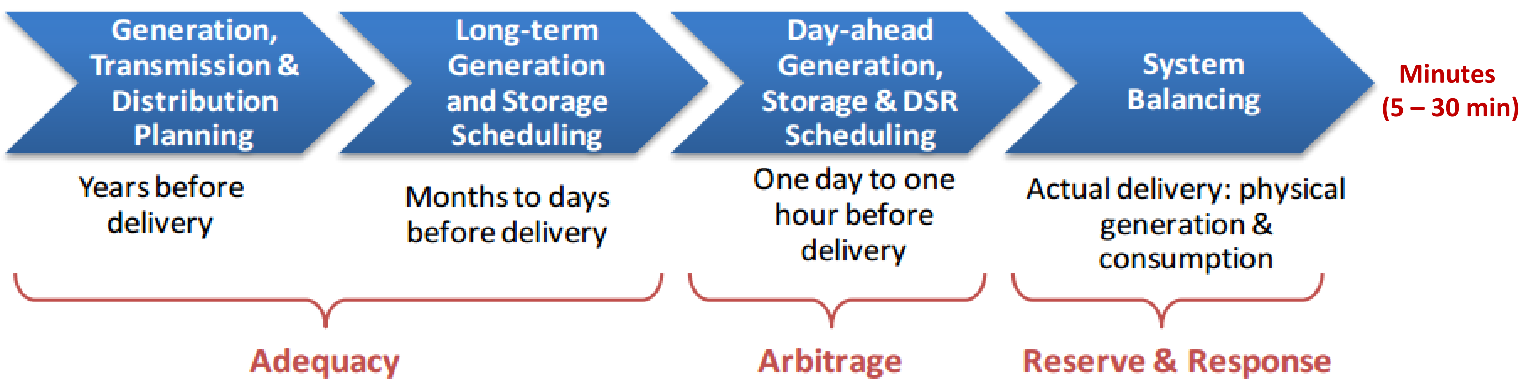
*An optimal operation model with endogenous investments on capacity and flexibility options*

**System cost and "multiple services" approach**: investment and operational costs

**Hydrothermal optimization**: when and how to use available hydro resources

**Operational constraints**: Ramping limits, min/max capacities, part-load efficiencies, etc.

**Reliability issues**: reserve requirements as a function of I-RES penetration




Source: Strbac. Imperial College London, 2012.

# 4. Model presentation

Any question so far?

# 4. Model presentation



**Total system cost represented as *Y* :**

$$
\begin{aligned}
\min Y = & \sum_{con} I_{con} + \sum_{con}\sum_{t}\left(O\&M_{con,t} + F_{con,t} + CO2_{con,t} + \Delta G_{con,t}\right) \\
& + \sum_{res} I_{RES} + \sum_{res}\sum_{t}\left(O\&M_{res,t} + REC_{res,t}\right) \\
& + \sum_{ees} I_{ees} + \sum_{ees}\sum_{t} O\&M_{ees,t} \\
& + \sum_{lc}\sum_{t} DSM_{lc,t} + \sum_{ls}\sum_{t} DSM_{ls,t}
\end{aligned}
$$

*MT*

*LT*

*ST*

*Subject to operational constraints and clean energy policies…*

But which ones and under what formulation?

# 4. Model presentation

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Palmintier. “**Flexibility in Generation Planning : Identifying Key Operating Constraints**”. PSCC 2014.

Variations

| ID# | config_code | maintenance | reserves | ramp | unit commitment | startup | min up/down time | derate | minimum planning margin | slove as LP | Speedup | Avg. Abs. Relative Cost Error | Avg. Abs. Relative CO2 Error | Capacity Error (RMS) | Energy Mix Error (RMS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Relative accuracy | | | |
| **0** | **full** | Y | sep | Y | Y | Y | Y | | 0.05 | | 1.0 | 0.0% | 0.0% | 0.0% | 0.0% |
| **1** | **simp** | | | | | | | Y | full | | 3832.8 | 6.1% | 10.9% | 48.8% | 56.3% |
| 2 | edRsv | Y | sep | | | | | | full | | 105.2 | 2.2% | 6.6% | 21.8% | 50.0% |
| 3 | uclp | Y | sep | Y | Y | Y | Y | | full | | 2.9 | 1.0% | 1.6% | 11.0% | 11.9% |
| 4 | noMaint | | sep | Y | Y | Y | Y | | full | | 1.0 | 3.8% | 6.3% | 18.7% | 30.2% |
| 5 | full_flex | Y | flex | Y | Y | Y | Y | | full | | 1.7 | 1.8% | 3.8% | 17.2% | 19.7% |
| 6 | noRsrv | Y | | Y | Y | Y | Y | | full | | 2.9 | 3.6% | 12.5% | 41.1% | 48.1% |
| 7 | noRamp | Y | sep | | Y | Y | Y | | full | | 0.8 | 0.5% | 1.9% | 7.3% | 9.5% |
| 8 | noStUp | Y | sep | Y | Y | | Y | | full | | 0.9 | 1.0% | 1.7% | 12.9% | 17.4% |
| 9 | noUpDn | Y | sep | Y | Y | Y | | | full | | 1.9 | 1.1% | 7.5% | 16.5% | 28.2% |
| **10** | **simp_noDerate** | | | | | | | | full | | 3743.6 | 7.7% | 20.0% | 35.3% | 64.5% |
| 11 | oMaint | Y | | | | | | Y | full | | 1227.9 | 2.9% | 14.1% | 44.2% | 48.7% |
| **12** | **oFlex** | | flex | | | | | Y | full | | 666.5 | 2.3% | 1.0% | 26.6% | 35.4% |
| 13 | oRamp | | | Y | | | | Y | full | | 1200.8 | 6.1% | 14.9% | 45.1% | 52.4% |
| 14 | oUC | | | | Y | | | Y | full | | 422.6 | 3.9% | 15.7% | 51.4% | 69.2% |
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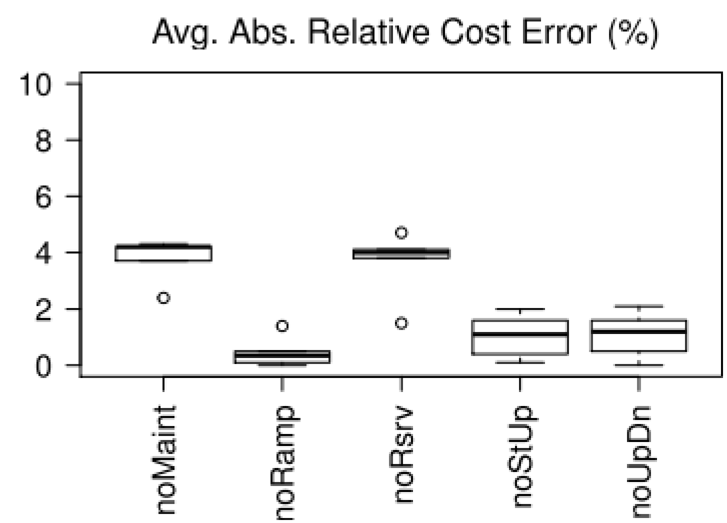
| 20 | MtFxUcRp | Y | flex | Y | Y | | | | full | | Did not reliably finish before timeout | | | | |
| 21 | MtFxUcRpL | Y | flex | Y | Y | | | | full | Y | 831.9 | 3.1% | 7.3% | 29.9% | 45.8% |
| 22 | oM_nDrt | Y | | | | | | | full | | 1109.1 | 4.6% | 19.7% | 47.6% | 69.1% |
| **23** | **FlxRmp** | | flex | Y | | | | Y | full | | 301.9 | 2.3% | 2.2% | 25.9% | 33.8% |
| **24** | **FxRpMt** | Y | flex | Y | | | | Y | full | | 173.8 | 2.1% | 3.8% | 24.7% | 31.0% |
| 25 | FxRpMt_nDrt | Y | flex | Y | | | | | full | | 75.8 | 1.5% | 3.6% | 31.2% | 49.0% |
| **26** | **FxRpMt_LnD** | Y | flex | Y | | | | | full | Y | 1730.5 | 1.4% | 3.8% | 32.4% | 49.1% |
| 27 | RpMt | Y | | Y | | | | Y | full | | 487.9 | 2.9% | 15.0% | 46.0% | 52.5% |
| 28 | RpMt_nDrt | Y | | Y | | | | | full | | 261.4 | 4.6% | 18.9% | 47.8% | 66.5% |
| **29** | **SepRmp** | | sep | Y | | | | Y | full | | 77.6 | 1.0% | 6.6% | 38.7% | 81.0% |
| 30 | SpRpMt | Y | sep | Y | | | | Y | full | | 77.1 | 3.5% | 16.6% | 42.8% | 85.1% |
| 31 | SpRpMt_nDrt | Y | sep | Y | | | | | full | | 26.7 | 2.3% | 6.7% | 22.4% | 51.3% |
| **32** | **SxRpMt_LnD** | Y | sep | Y | | | | | full | Y | 1510.0 | 2.1% | 7.5% | 23.1% | 52.4% |
| **33** | **lp** | Y | sep | Y | Y | Y | Y | | full | Y | 53.4 | 1.1% | 0.8% | 9.3% | 8.4% |
| **34** | **lpNpm** | Y | sep | Y | Y | Y | Y | | 0.05 | Y | 42.0 | 0.9% | 0.7% | 9.8% | 8.6% |
| 35 | FxUcNpm | | flex | | Y | | | Y | 0.05 | | 1.5 | 2.2% | 4.4% | 28.7% | 35.3% |
| 36 | MtFxUcNpm | Y | flex | | Y | | | | 0.05 | | 1.5 | 3.3% | 7.3% | 33.9% | 39.0% |
| 37 | MtFxUcRpNpm | Y | flex | Y | Y | | | | 0.05 | | Did not reliably finish before timeout | | | | |
| **38** | **MtFxUcRpLNpm** | Y | flex | Y | Y | | | | 0.05 | Y | 546.5 | 3.9% | 5.7% | 33.0% | 34.0% |
| **39** | **simpNpm** | | | | | | | Y | 0.05 | | 3204.9 | 7.1% | 9.5% | 43.5% | 39.6% |
| 40 | simpNpm_nDrt | | | | | | | | 0.05 | | 3343.7 | 9.3% | 12.9% | 46.9% | 56.0% |
| 41 | oMaintNpm | Y | | | | | | Y | 0.05 | | 1171.1 | 3.9% | 9.0% | 46.3% | 44.3% |
| **42** | **oFlexNpm** | | flex | | | | | Y | 0.05 | | 488.4 | 2.3% | 0.7% | 24.6% | 35.9% |
| 43 | oRampNpm | | | Y | | | | Y | 0.05 | | 1316.8 | 7.1% | 9.5% | 43.5% | 39.9% |
| 44 | oUC_Npm | | | | Y | | | Y | 0.05 | | Did not reliably finish before timeout | | | | |
| 45 | FlxRmpNpm | | flex | Y | | | | Y | 0.05 | | 247.5 | 2.3% | 1.5% | 24.1% | 34.8% |
| 46 | FxRpMt_nDrtNpm | Y | flex | Y | | | | | 0.05 | | 62.1 | 2.0% | 1.7% | 34.7% | 57.9% |
| **47** | **FxRpMt_LnD_Npm** | Y | flex | Y | | | | | 0.05 | Y | 1778.1 | 1.8% | 1.8% | 33.9% | 55.5% |
| 48 | SepRmpNpm | | sep | Y | | | | Y | 0.05 | | 111.4 | 1.5% | 5.2% | 48.6% | 89.8% |
| 49 | SpRpMt_nDrtNpm | Y | sep | Y | | | | | 0.05 | | 46.0 | 2.5% | 7.4% | 38.4% | 66.4% |
| 50 | SxRpMt_LnD_Npm | Y | sep | Y | | | | | 0.05 | Y | 1398.0 | 2.4% | 7.2% | 37.6% | 65.1% |

FULL = Complete MILP formulation with unit clustering 8760h:
MIP gap = 0.1% => solution time > 60h

- **50 combinations of UC+Maintenance+Planning**
- **MILP relaxations are considered for each variation**




Source: Palmintier, 2014.

# 4. Model presentation

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Palmintier. "**Flexibility in Generation Planning : Identifying Key Operating Constraints**". PSCC 2014.

**Palmintier's formulation:**

- No EES or DSM considered
- No endogenous investments on RES
- Deterministic reserve dimensioning

FULL = Complete MILP formulation with unit clustering 8760h:
MIP gap = 0.1% => solution time > 60h

- 50 combinations of UC+Maintenance+Planning
- Relaxations are considered for ... variation

$$Y = \sum_{con} I_{con} + \sum_{con}\sum_{t}\left(O\&M_{con,t} + F_{con,t} + CO2_{con,t} + \Delta G_{con,t}\right)$$

$$+ \sum_{res} I_{RES} + \sum_{res}\sum_{t}\left(O\&M_{res,t} + REC_{res,t}\right)$$

$$+ \sum_{ees} I_{ees} + \sum_{ees}\sum_{t} O\&M_{ees,t}$$

$$+ \sum_{lc}\sum_{t} DSM_{lc,t} + \sum_{ls}\sum_{t} DSM_{ls,t}$$

variations

| ID# | config code | maintenance | reserves | ramp | unit commitment | startup | up/dn time | separate | planning | same as LP | speedup | Avg. Abs. Relative Cost Error | Max Abs. Relative Error | Capacity (RMS) | Energy Mix Error (RMS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | full | Y | sep | Y | Y | Y | Y | | 0.05 | | 1.0 | 0.0% | 0.0% | 0.0% | 0.0% |
| 3 | uclp | Y | sep | Y | Y | Y | Y | | full | | 2.9 | 1.0% | 1.6% | 11.0% | 11.9% |
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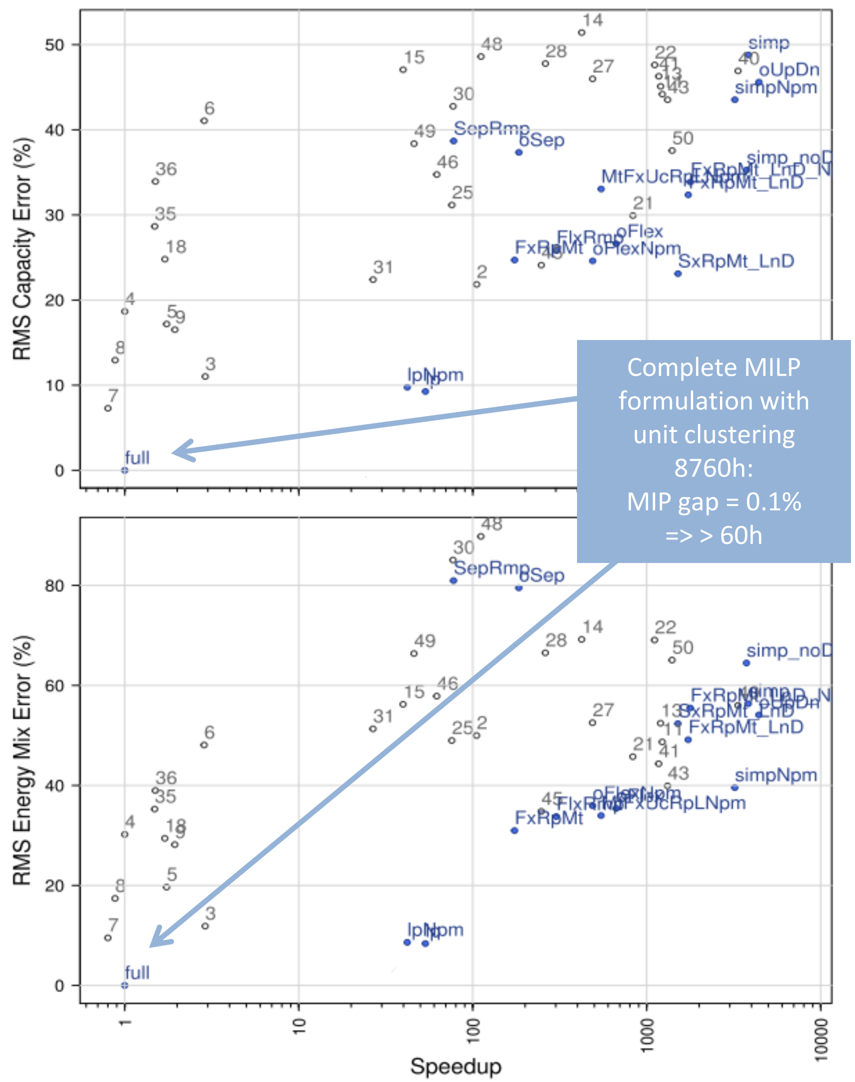
| **29** | **SepRmp** | | sep | Y | | | | Y | full | | 77.6 | 1.0% | 6.6% | 38.7% | 81.0% |
| 30 | SpRpMt | Y | sep | Y | | | | Y | full | | 77.1 | 3.5% | 16.6% | 42.8% | 85.1% |
| 31 | SpRpMt_nDrt | Y | sep | Y | | | | | full | | 26.7 | 2.3% | 6.7% | 22.4% | 51.3% |
| **32** | **SxRpMt_LnD** | Y | sep | Y | | | | | full | Y | 1510.0 | 2.1% | 7.5% | 23.1% | 52.4% |
| **33** | **lp** | Y | sep | Y | Y | Y | Y | | full | Y | 53.4 | 1.1% | 0.8% | 9.3% | 8.4% |
| **34** | **lpNpm** | Y | sep | Y | Y | Y | Y | | 0.05 | Y | 42.0 | 0.9% | 0.7% | 9.8% | 8.6% |
| 35 | FxUcNpm | | flex | | Y | | | Y | 0.05 | | 1.5 | 2.2% | 4.4% | 28.7% | 35.3% |
| 36 | MtFxUcNpm | Y | flex | | Y | | | | 0.05 | | 1.5 | 3.3% | 7.3% | 33.9% | 39.0% |
| 37 | MtFxUcRpNpm | Y | flex | Y | Y | | | | 0.05 | | Did not reliably finish before timeout | | | | |
| **38** | **MtFxUcRpLNpm** | Y | flex | Y | Y | | | | 0.05 | Y | 546.5 | 3.9% | 5.7% | 33.0% | 34.0% |
| **39** | **simpNpm** | | | | | | | Y | 0.05 | | 3204.9 | 7.1% | 9.5% | 43.5% | 39.6% |
| 40 | simpNpm_nDrt | | | | | | | | 0.05 | | 3343.7 | 9.3% | 12.9% | 46.9% | 56.0% |
| 41 | oMaintNpm | Y | | | | | | Y | 0.05 | | 1171.1 | 3.9% | 9.0% | 46.3% | 44.3% |
| **42** | **oFlexNpm** | | flex | | | | | Y | 0.05 | | 488.4 | 2.3% | 0.7% | 24.6% | 35.9% |
| 43 | oRampNpm | | | Y | | | | Y | 0.05 | | 1316.8 | 7.1% | 9.5% | 43.5% | 39.9% |
| 44 | oUC_Npm | | | | Y | | | Y | 0.05 | | Did not reliably finish before timeout | | | | |
| 45 | FlxRmpNpm | | flex | Y | | | | Y | 0.05 | | 247.5 | 2.3% | 1.5% | 24.1% | 34.8% |
| 46 | FxRpMt_nDrtNpm | Y | flex | Y | | | | | 0.05 | | 62.1 | 2.0% | 1.7% | 34.7% | 57.9% |
| **47** | **FxRpMt_LnD_Npm** | Y | flex | Y | | | | | 0.05 | Y | 1778.1 | 1.8% | 1.8% | 33.9% | 55.5% |
| 48 | SepRmpNpm | | sep | Y | | | | Y | 0.05 | | 111.4 | 1.5% | 5.2% | 48.6% | 89.8% |
| 49 | SpRpMt_nDrtNpm | Y | sep | Y | | | | | 0.05 | | 46.0 | 2.5% | 7.4% | 38.4% | 66.4% |
| 50 | SxRpMt_LnD_Npm | Y | sep | Y | | | | | 0.05 | Y | 1398.0 | 2.4% | 7.2% | 37.6% | 65.1% |




Source: Palmintier, 2014.

# 4. Model presentation

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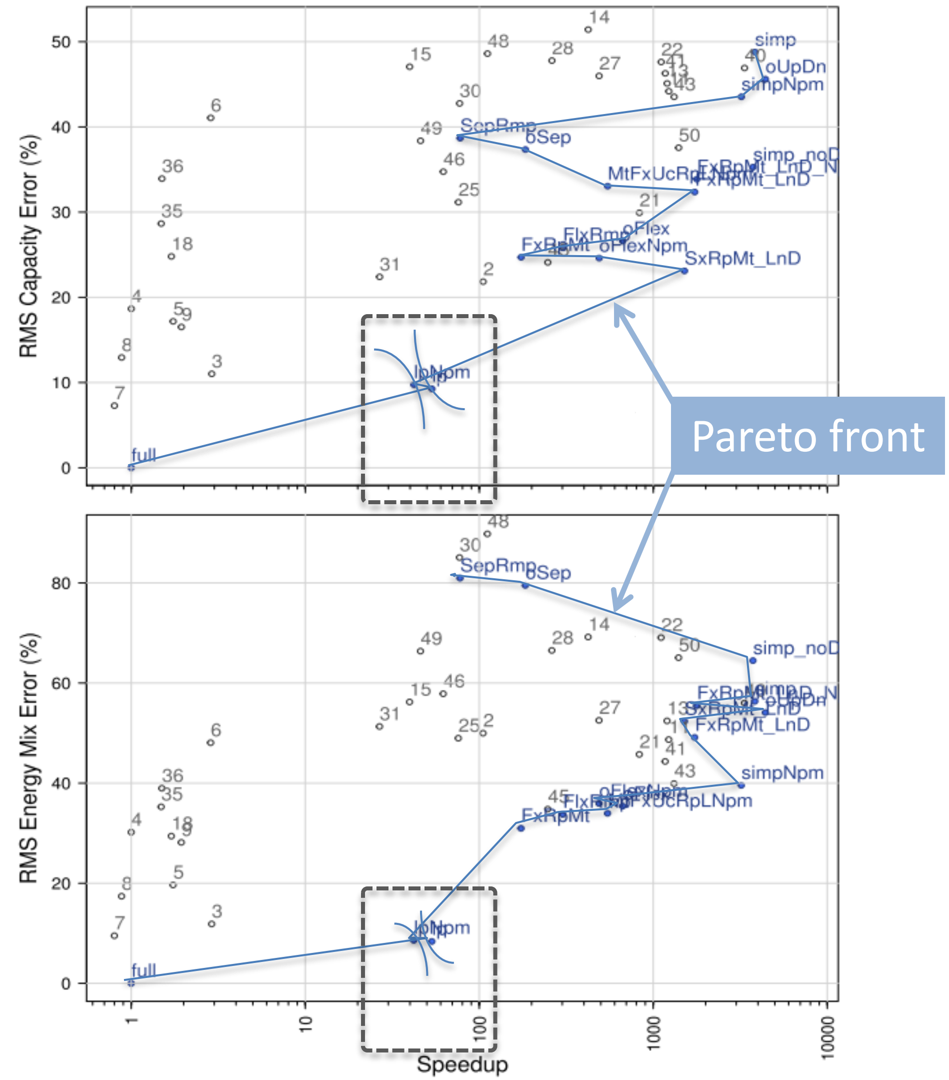
Palmintier. "**Flexibility in Generation Planning : Identifying Key Operating Constraints**". PSCC 2014.

variations

| ID# | config_code | maintenance | reserves | ramp | unit commitment | startup | min up/down time | derate | minimum planning margin | slove as LP | Speedup | Avg. Abs. Relative Cost Error | Avg. Abs. Relative CO2 Error | Capacity Error (RMS) | Energy Mix Error (RMS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Relative accuracy | | | |
| **0** | **full** | Y | sep | Y | Y | Y | Y | | 0.05 | | 1.0 | 0.0% | 0.0% | 0.0% | 0.0% |
| **1** | **simp** | | | | | | | Y | full | | 3832.8 | 6.1% | 10.9% | 48.8% | 56.3% |
| 2 | edRsv | Y | sep | | | | | | full | | 105.2 | 2.2% | 6.6% | 21.8% | 50.0% |
| 3 | uclp | Y | sep | Y | Y | Y | Y | | full | | 2.9 | 1.0% | 1.6% | 11.0% | 11.9% |
| 4 | noMaint | | sep | Y | Y | Y | Y | | full | | 1.0 | 3.8% | 6.3% | 18.7% | 30.2% |
| 5 | full_flex | Y | flex | Y | Y | Y | Y | | full | | 1.7 | 1.8% | 3.8% | 17.2% | 19.7% |
| 6 | noRsrv | Y | | Y | Y | Y | Y | | full | | 2.9 | 3.6% | 12.5% | 41.1% | 48.1% |
| 7 | noRamp | Y | sep | | Y | Y | Y | | full | | 0.8 | 0.5% | 1.9% | 7.3% | 9.5% |
| 8 | noStUp | Y | sep | Y | Y | | Y | | full | | 0.9 | 1.0% | 1.7% | 12.9% | 17.4% |
| 9 | noUpDn | Y | sep | Y | Y | Y | | | full | | 1.9 | 1.1% | 7.5% | 16.5% | 28.2% |
| **10** | **simp_noDerate** | | | | | | | | full | | 3743.6 | 7.7% | 20.0% | 35.3% | 64.5% |
| 11 | oMaint | Y | | | | | | Y | full | | 1227.9 | 2.9% | 14.1% | 44.2% | 48.7% |
| **12** | **oFlex** | | flex | | | | | Y | full | | 666.5 | 2.3% | 1.0% | 26.6% | 35.4% |
| 13 | oRamp | | | Y | | | | Y | full | | 1200.8 | 6.1% | 14.9% | 45.1% | 52.4% |
| 14 | oUC | | | | Y | | | Y | full | | 422.6 | 3.9% | 15.7% | 51.4% | 69.2% |
| 15 | oStUp | | | | | Y | | Y | full | | 39.8 | 3.5% | 9.7% | 47.1% | 56.2% |
| **16** | **oUpDn** | | | | | | Y | Y | full | | 4408.7 | 6.1% | 15.3% | 45.6% | 54.1% |
| **17** | **oSep** | | sep | | | | | Y | full | | 184.0 | 1.0% | 6.5% | 37.3% | 79.5% |
| 18 | FxUc | | flex | | Y | | | Y | full | | 1.7 | 1.6% | 4.4% | 24.8% | 29.4% |
| 19 | MtFxUc | Y | flex | | Y | | | | full | | Did not reliably finish before timeout | | | | |
| 20 | MtFxUcRp | Y | flex | Y | Y | | | | full | | Did not reliably finish before timeout | | | | |
| 21 | MtFxUcRpL | Y | flex | Y | Y | | | | full | Y | 831.9 | 3.1% | 7.3% | 29.9% | 45.8% |
| 22 | oM_nDrt | Y | | | | | | | full | | 1109.1 | 4.6% | 19.7% | 47.6% | 69.1% |
| **23** | **FlxRmp** | | flex | Y | | | | Y | full | | 301.9 | 2.3% | 2.2% | 25.9% | 33.8% |
| **24** | **FxRpMt** | Y | flex | Y | | | | Y | full | | 173.8 | 2.1% | 3.8% | 24.7% | 31.0% |
| 25 | FxRpMt_nDrt | Y | flex | Y | | | | | full | | 75.8 | 1.5% | 3.6% | 31.2% | 49.0% |
| **26** | **FxRpMt_LnD** | Y | flex | Y | | | | | full | Y | 1730.5 | 1.4% | 3.8% | 32.4% | 49.1% |
| 27 | RpMt | Y | | Y | | | | Y | full | | 487.9 | 2.9% | 15.0% | 46.0% | 52.5% |
| 28 | RpMt_nDrt | Y | | Y | | | | | full | | 261.4 | 4.6% | 18.9% | 47.8% | 66.5% |
| **29** | **SepRmp** | | sep | Y | | | | Y | full | | 77.6 | 1.0% | 6.6% | 38.7% | 81.0% |
| 30 | SpRpMt | Y | sep | Y | | | | Y | full | | 77.1 | 3.5% | 16.6% | 42.8% | 85.1% |
| 31 | SpRpMt_nDrt | Y | sep | Y | | | | | full | | 26.7 | 2.3% | 6.7% | 22.4% | 51.3% |
| **32** | **SxRpMt_LnD** | Y | sep | Y | | | | | full | Y | 1510.0 | 2.1% | 7.5% | 23.1% | 52.4% |
| **33** | **lp** | Y | sep | Y | Y | Y | Y | | full | Y | 53.4 | 1.1% | 0.8% | 9.3% | 8.4% |
| **34** | **lpNpm** | Y | sep | Y | Y | Y | Y | | 0.05 | Y | 42.0 | 0.9% | 0.7% | 9.8% | 8.6% |
| 35 | FxUcNpm | | flex | | Y | | | Y | 0.05 | | 1.5 | 2.2% | 4.4% | 28.7% | 35.3% |
| 36 | MtFxUcNpm | Y | flex | | Y | | | | 0.05 | | 1.5 | 3.3% | 7.3% | 33.9% | 39.0% |
| 37 | MtFxUcRpNpm | Y | flex | Y | Y | | | | 0.05 | | Did not reliably finish before timeout | | | | |
| **38** | **MtFxUcRpLNpm** | Y | flex | Y | Y | | | | 0.05 | Y | 546.5 | 3.9% | 5.7% | 33.0% | 34.0% |
| **39** | **simpNpm** | | | | | | | Y | 0.05 | | 3204.9 | 7.1% | 9.5% | 43.5% | 39.6% |
| 40 | simpNpm_nDrt | | | | | | | | 0.05 | | 3343.7 | 9.3% | 12.9% | 46.9% | 56.0% |
| 41 | oMaintNpm | Y | | | | | | Y | 0.05 | | 1171.1 | 3.9% | 9.0% | 46.3% | 44.3% |
| **42** | **oFlexNpm** | | flex | | | | | Y | 0.05 | | 488.4 | 2.3% | 0.7% | 24.6% | 35.9% |
| 43 | oRampNpm | | | Y | | | | Y | 0.05 | | 1316.8 | 7.1% | 9.5% | 43.5% | 39.9% |
| 44 | oUC_Npm | | | | Y | | | Y | 0.05 | | Did not reliably finish before timeout | | | | |
| 45 | FlxRmpNpm | | flex | Y | | | | Y | 0.05 | | 247.5 | 2.3% | 1.5% | 24.1% | 34.8% |
| 46 | FxRpMt_nDrtNpm | Y | flex | Y | | | | | 0.05 | | 62.1 | 2.0% | 1.7% | 34.7% | 57.9% |
| **47** | **FxRpMt_LnD_Npm** | Y | flex | Y | | | | | 0.05 | Y | 1778.1 | 1.8% | 1.8% | 33.9% | 55.5% |
| 48 | SepRmpNpm | | sep | Y | | | | Y | 0.05 | | 111.4 | 1.5% | 5.2% | 48.6% | 89.8% |
| 49 | SpRpMt_nDrtNpm | Y | sep | Y | | | | | 0.05 | | 46.0 | 2.5% | 7.4% | 38.4% | 66.4% |
| 50 | SxRpMt_LnD_Npm | Y | sep | Y | | | | | 0.05 | Y | 1398.0 | 2.4% | 7.2% | 37.6% | 65.1% |

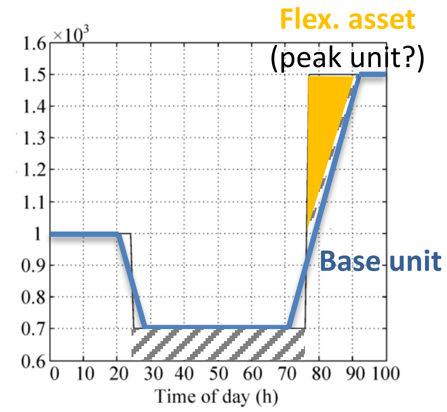



Source: Palmintier, 2014.

# 4. Model presentation

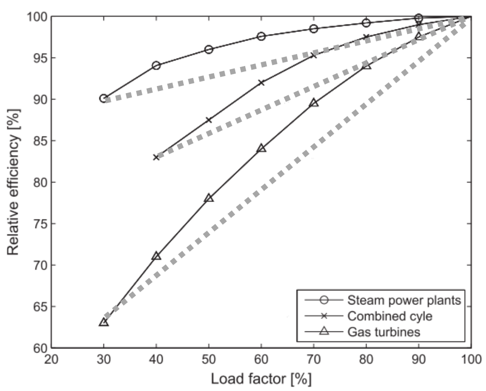
## Modeling issues when adopting LP formulations:

- **Min power limits**: when using a technology based dispatch and Pmin > 0, it implicitly contains must-run obligations which are not convenient to schedule peak and extreme peak units.




- **Ramping constraints issues**: technology ramping in MW/min can overestimate real ramping capabilities on hourly scheduling.

- **Part load efficiencies**: non-linear by nature they use to be step-wise linearized or linearly approximated, thus, overestimating fuel consumption and $CO_2$ emissions.



# 4. Model presentation

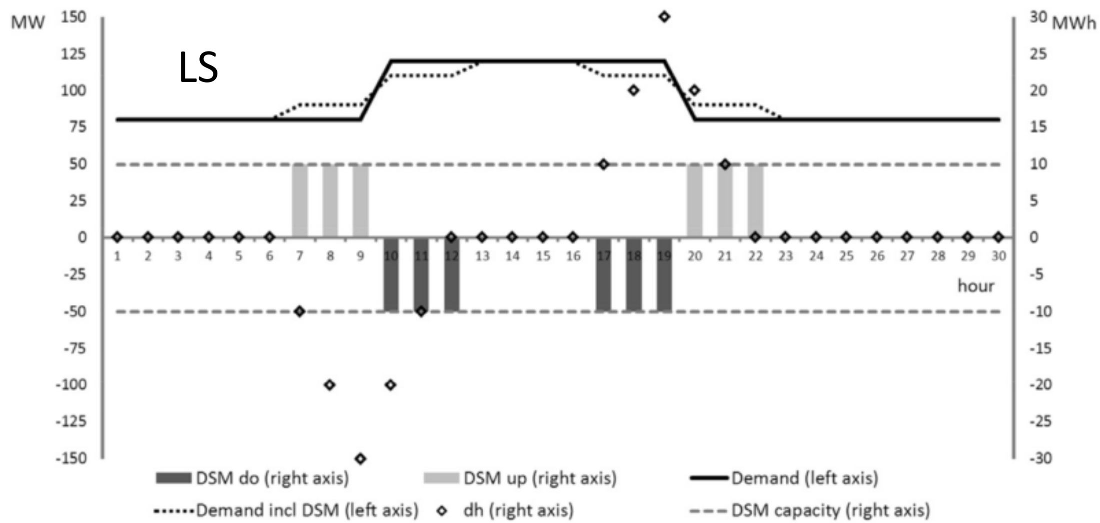
**Modeling issues for representing flexibility assets:**

- **EES technologies**:
  - Investments:  energy and capacity should be separately optimized.
  - Operation: Constrained by installed capacity but also by energy stock (path dependence)

- **DSM operation**: Using the “virtual stock analogy” to model load shifting (LS) is insufficient

=> the “debit/credit moving window” formulation (*Zerranh and Schill, 2015*) was adopted

*e.x:* ~~*stock(t=0) = 0*~~

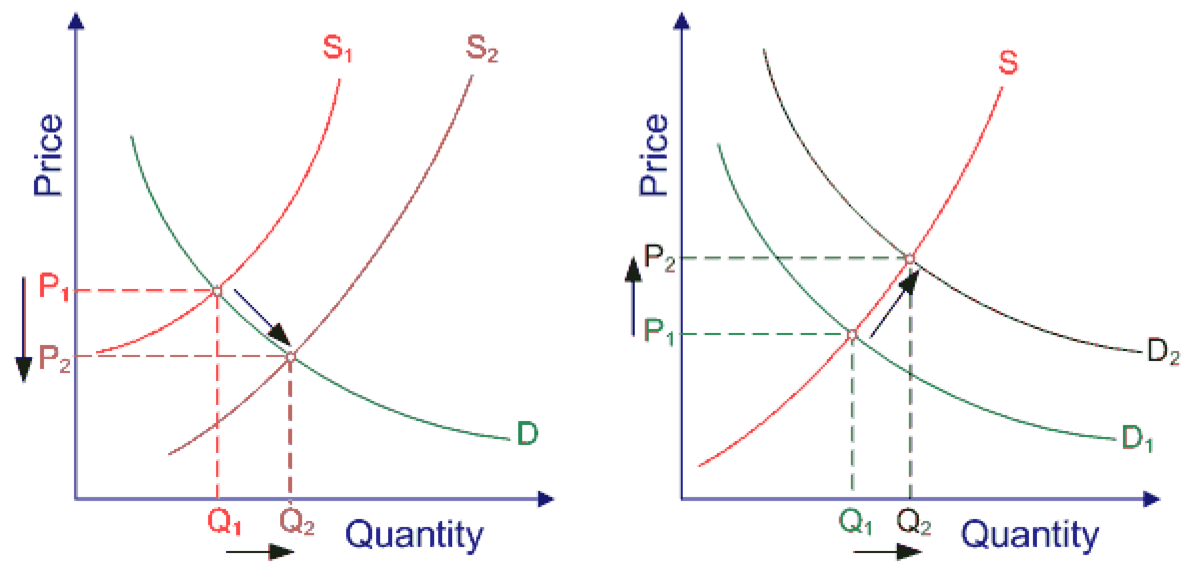



Source: Zerranh and Schill, 2015.

# 4. Model presentation

**Balancing demand and supply:**

**J-1 market for time delivery *t***




$$\mathrm{L}_{\mathrm{t}}^{\mathrm{base}}\,(1+\delta) - \sum_{res} \left( G^{l}{}_{res,t} \qquad\qquad \right) = \sum_{con} G_{con,t}^{sync} \qquad \forall\, t$$

# 4. Model presentation

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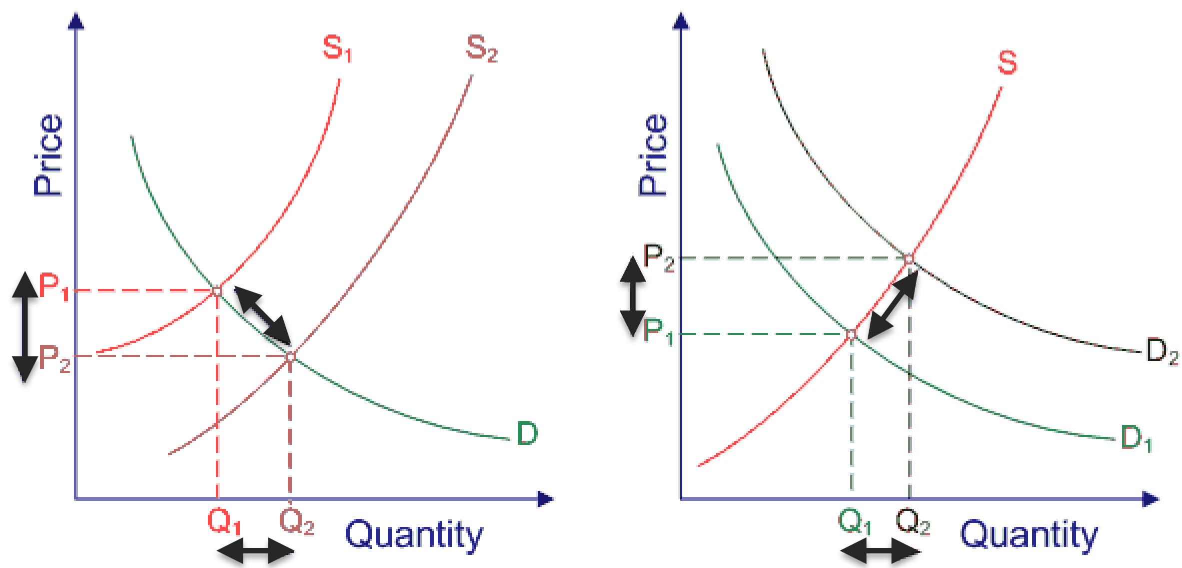
## Balancing flexible demand and flexible supply:

**J-1 market for time delivery *t***

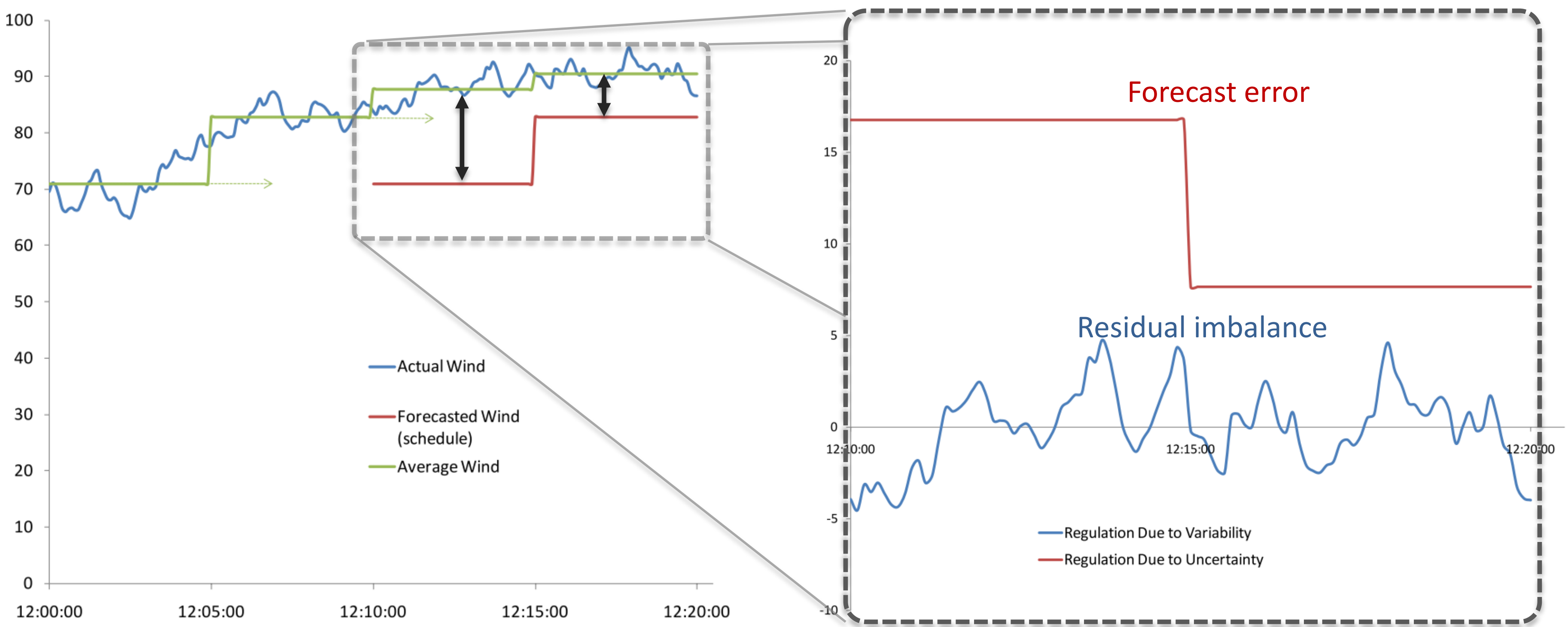



$$L_t^{base}(1+\delta) - \sum_{res}\left(G^{l}{}_{res,t} - G^{cu}{}_{res,t}\right) = \sum_{con} G^{sync}_{con,t} + \sum_{ees}\left(S^{dch}_{ees,t} - S^{ch}_{ees,t}\right) + \sum_{lc} DSM^{l}{}_{lc,t} + \sum_{ls}\sum_{tt=t-L_{ls}}^{tt=t+L_{ls}} DSM^{do}_{ls,tt,t} - \sum_{ls} DSM^{up}_{ls,t} \quad \forall\, t$$

*with path dependent flexibility assets*

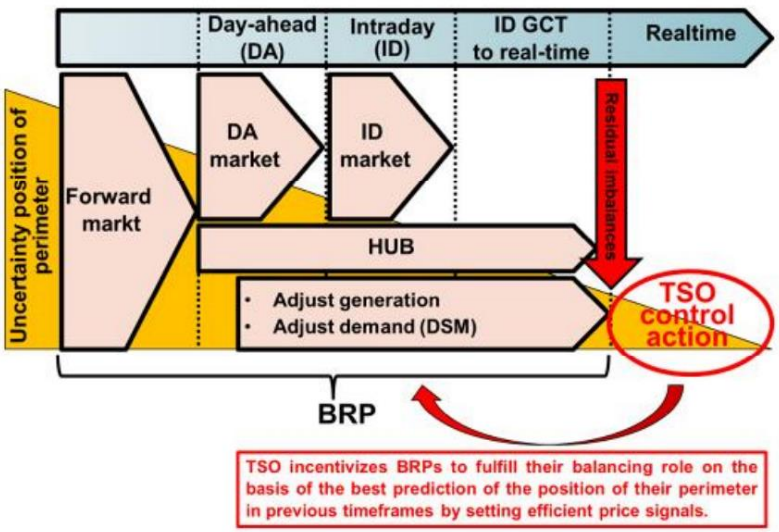
# 4. Model presentation

## Accounting for variability and uncertainty of net demand

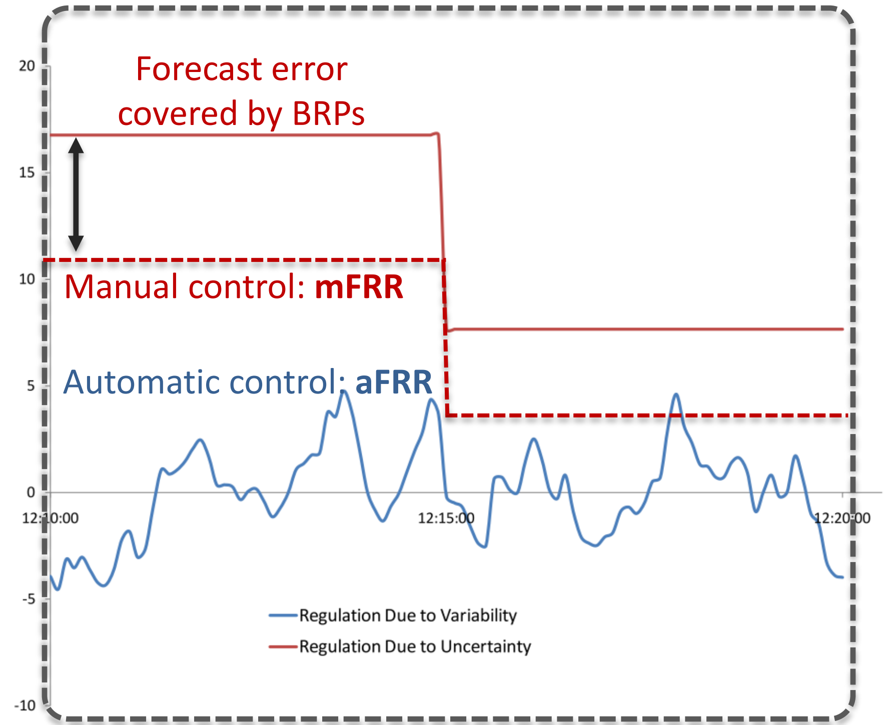



Source: NREL 2011, "Operating Reserves and Variable Generation"

**Regulating actions to control variability and uncertainty of net demand**




Source: ELIA, 2012.




Source: NREL 2011, “Operating Reserves and Variable Generation”

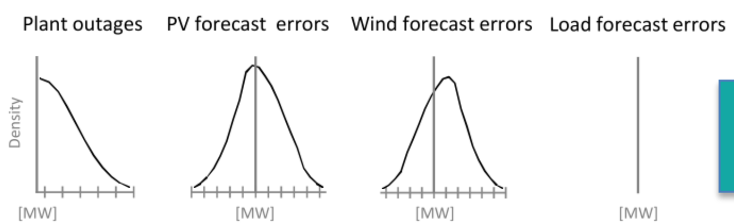
# 4. Model presentation

**But how much FRR is required?**

Probabilistic vs. deterministic methodologies for dimensioning FRR

**Deterministic method:** $FRR = \sqrt{10\,L_{max} + 150^2} - 150$

**Probabilistic method:** based on the recursive convolution method of residual system imbalances

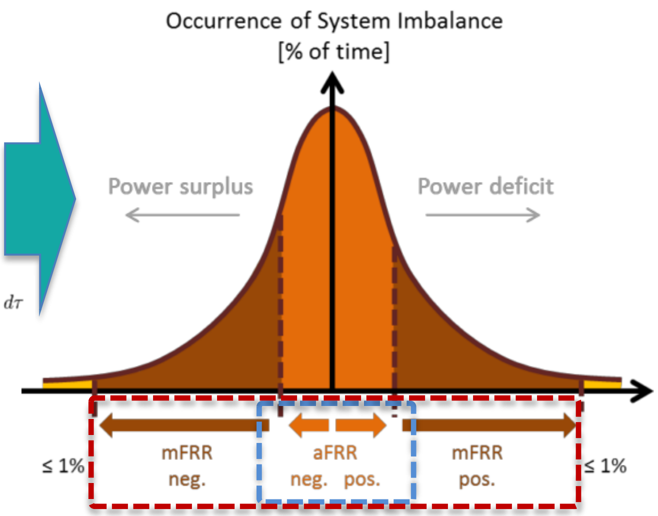



Source: Hirth & Ziegenhagen, 2013. Control Power and Variable Renewables: A Glimpse at German Data

1. Normalisation: 1/Cap

2. Convolution:

$$(f * g)(t) \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f(\tau)\, g(t-\tau)\, d\tau$$

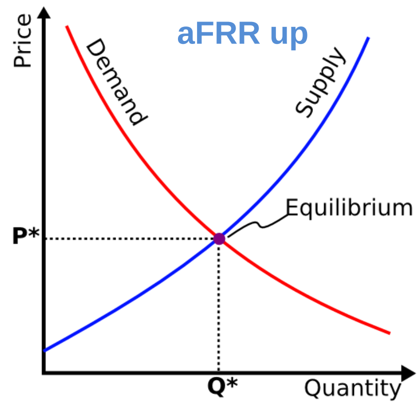


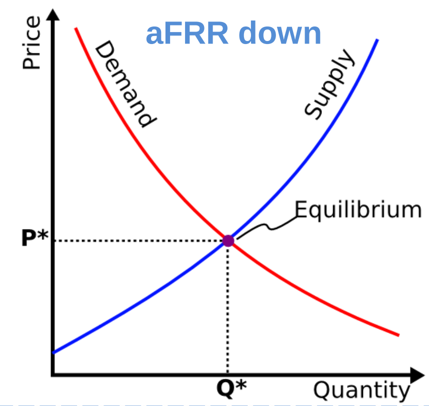

Source: Stiphout, 2014. FRR dimensioning based on ELIA methodology, 2012

# 4. Model presentation

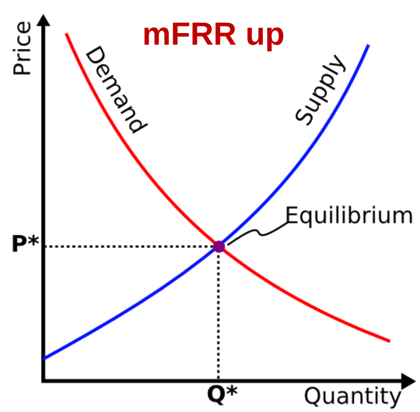
## Not-event secondary control: four services required

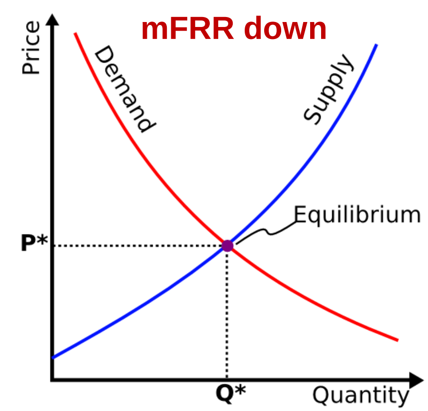
**Online units only + EES**




**All spinning and non-spinning units**



# 4. Model presentation



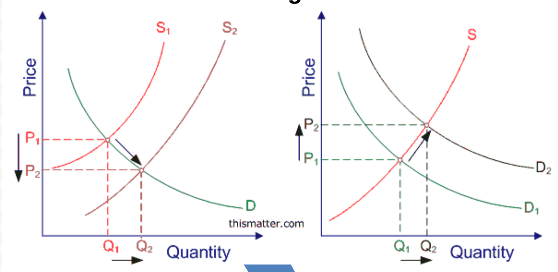
*LT*

## Optimal investments

**Investments:** set installed capacity (I-RES, conventionals, EES) and fixed cost

**Defines annual net load**
**Defines reserve requirements**

*MT*




## Optimal schedule

**Optimal scheduling** of available capacity (generation, EES and DSM) regarding operational constraints and variable cost

## *Min Total Cost*

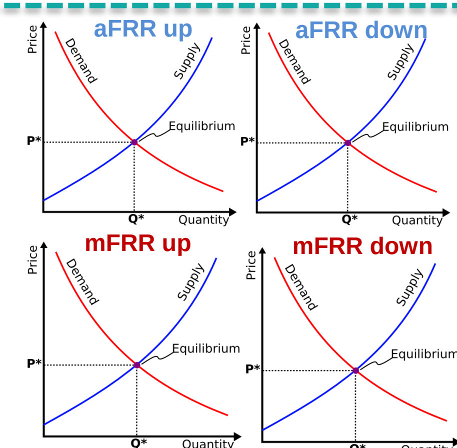
*Optimal investments*
*Optimal dispatch*
*Optimal reserve supply*

**Assets competing to supply multiple services**

*ST*

## Balancing FRR

Verifying reliability compliance given dispatched unit regulating capabilities



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## Experimental setup:

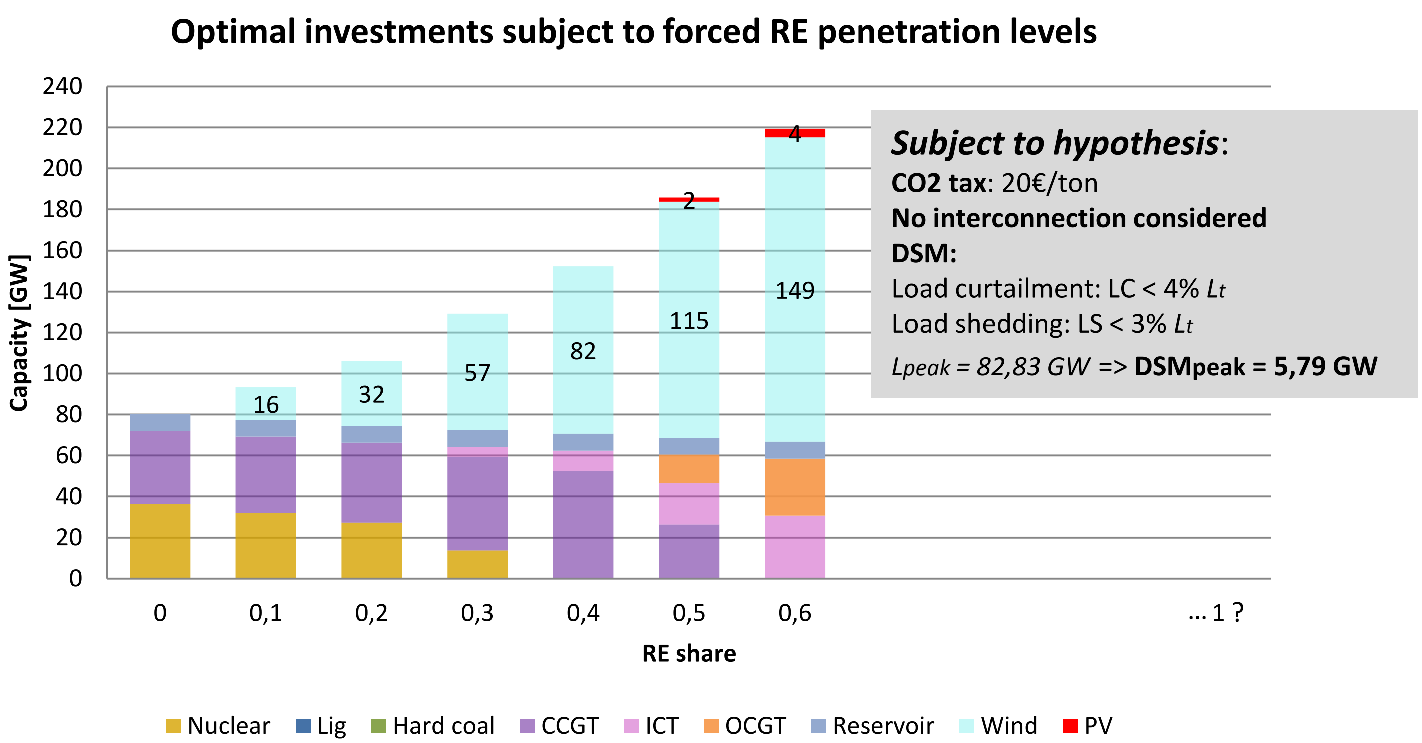
- **Perimeter and dataset: France 2013 used as the base year** (load, I-RES capacity factors, etc.) with increasing **RE shares (0-60%)**.
- **Hourly time step and 8760 hours** (a year) to be simulated.
- **Considered portfolio of technologies:** investment and operation
  - **Generation** (endogenous)**:** Nuclear, reservoir hydro, coal, CCGT, OCGT, ICT (high peak), wind and solar (including curtailment)
  - **Other RES** (exogenous): Fatal hydro, Biomass, etc.
  - **Bulk storage** (endogenous): PHS, CAES, VRFB, NaS, Li-ion
  - **DSM**: Load curtailment (LC < 4% of $L_t$) and load shedding (LS < 3% of $L_t$) capabilities
- **Cost and parameters**: compiled from reports of DIW, Black and Veatch, IEA, EPRI, NREL and other technical publications.

Solved on GAMS under CPLEX 12.5 using the barrier algorithm

# 4. Model results: optimal mix with increasing I-RES shares

**Considering the "stringent" operating reserve:**

- Assumed CO2 tax and DSM level led to an optimal system composed only by Nuclear, CCGT, reservoir hydro (RE_share = 0).
- Generation technologies and DSM supplies enough flexibility to the system, thus, no investments in EES are required on any of the scenarios.
- There is a progressive substitution of baseload investments towards more peaking units enabling the supply of higher flexibility needs and the operating reserve (spinning and no spinning).



# 4. Model results: optimal mix with increasing I-RES shares

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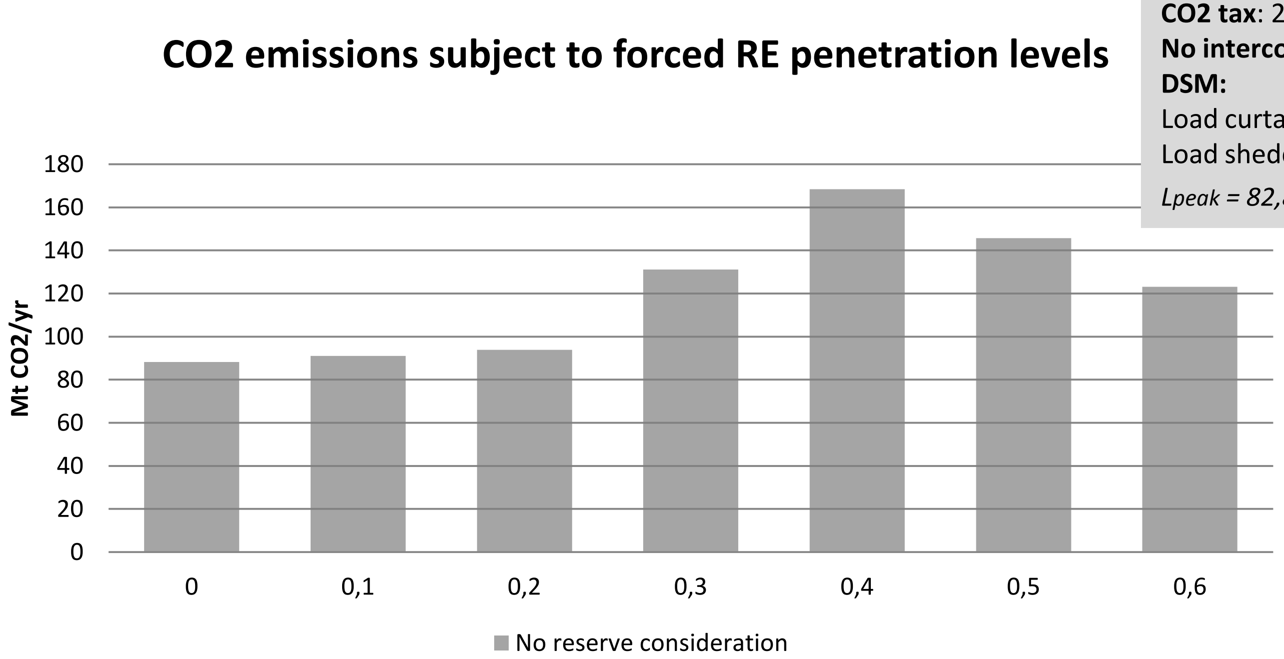
**Considering the "stringent" operating reserve:**

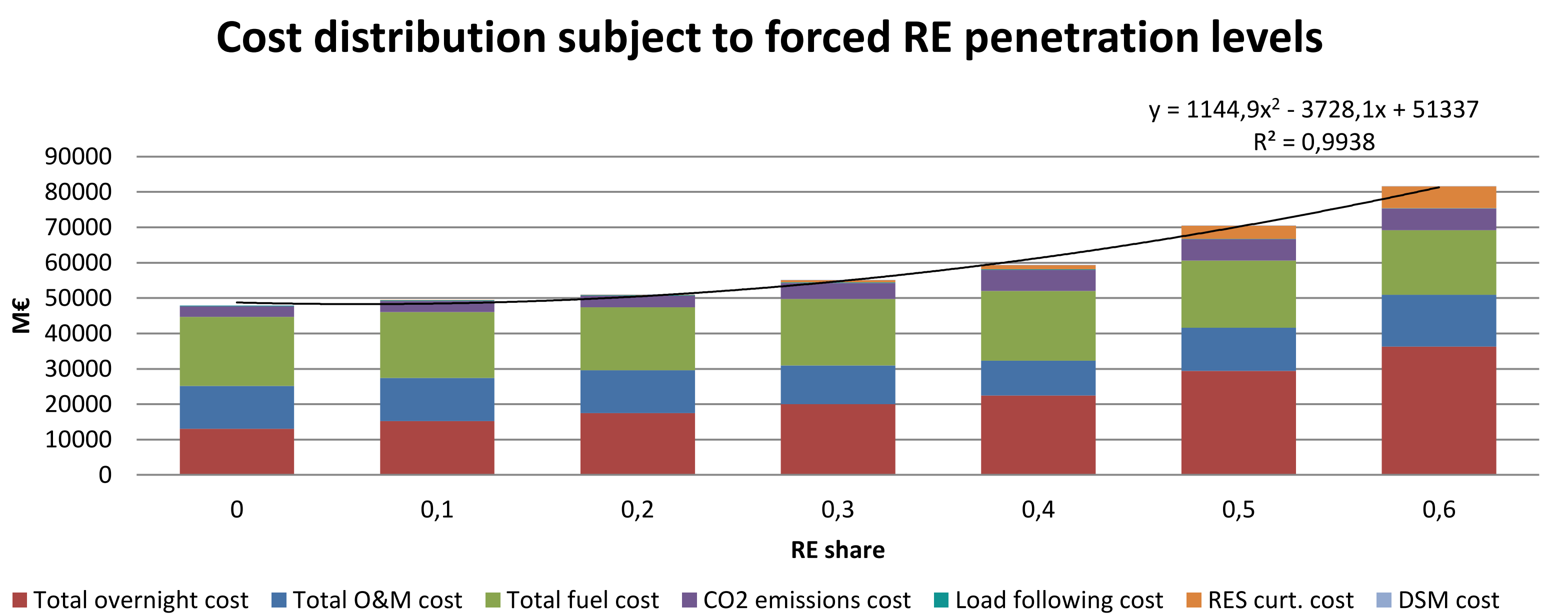
- The switch to higher $CO_2$ emission fuels to supply still important levels of base load makes no clear $CO_2$ savings until RE shares reach 40%.
- At higher RE penetration, there are $CO_2$ savings due to the more relaxed minimum generation level of high peak units present on the mix but at the expenses of higher RE curtailment.
- Stringent $CO_2$ emissions penalties should be required to incite $CO_2$ savings (triggering investments on EES?).

***Subject to hypothesis***:
**CO2 tax**: 20€/ton
**No interconnections considered**
**DSM:**
Load curtailment: LC < 4% $L_t$
Load shedding: LS < 3% $L_t$
*Lpeak = 82,83 GW* => **DSMpeak = 5,79 GW**



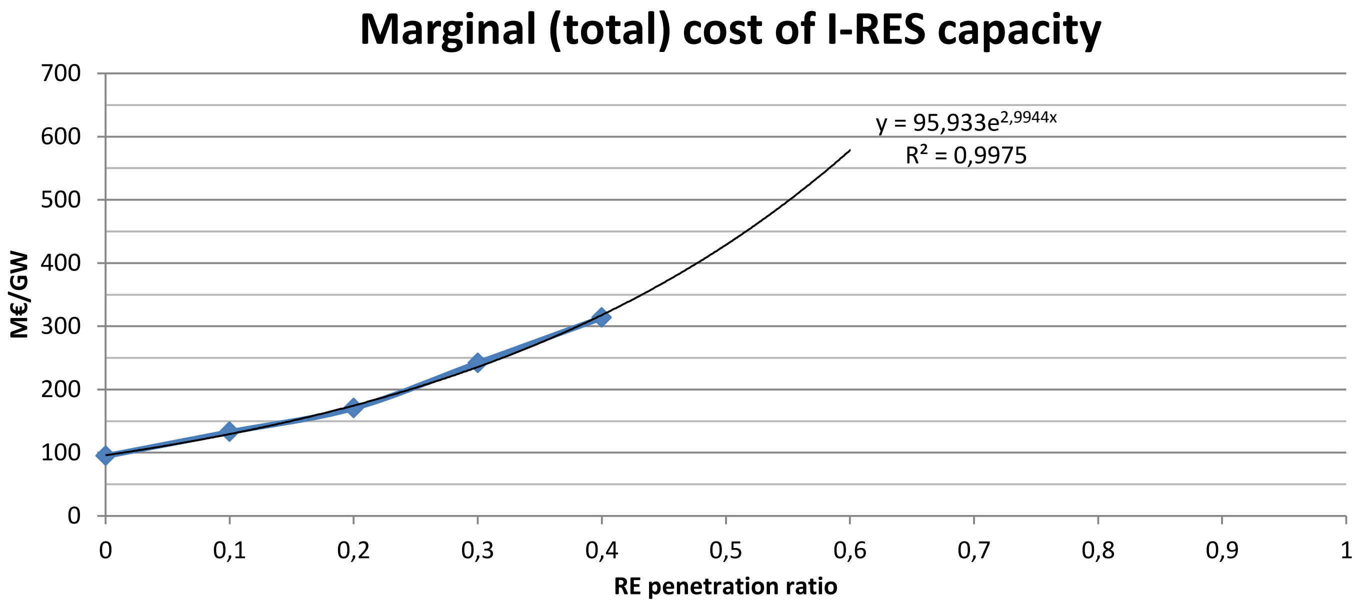
**Considering the "stringent" operating reserve:**

- When increasing the RE share there is less energy produced by conventionals, but this is done by using less efficient units. Hence, no clear CO2 cost savings.
- Fuel savings (fuel quantity) are eclipsed due to the switching to higher cost fuels (fuel quality), then, there are no net savings on total fuel costs.
- O&M costs remain at the same level because variable O&M savings (less energy produced) are compensated by fixed ones (greater fleet) and increased cycling cost of conventionals.
- Higher overnight cost due to required higher investments on I-RES capacity.



**Considering the "stringent" operating reserve:**

$$\mathrm{MTC}_{i-res} = \frac{\Delta Y}{\Delta IRES}$$



# 4. Model results: optimal mix with increasing I-RES shares

**Considering the "stringent" operating reserve:**

- Increasing electricity prices and price volatility
- What level to the VOLL?

| *Statistics* | *RE 0,0* | *RE 0,2* | *RE 0,4* | *RE 0,6* |
|---|---|---|---|---|
| ***Average*** | ***89*** | ***140*** | ***199*** | ***301*** |
| Median | 81,0 | 133,1 | 215,8 | 429,3 |
| q1 | 63,8 | 118,1 | 206,5 | -82,0 |
| min | -65,8 | -82,0 | -82,0 | -97,0 |
| max | 13395 | 19950 | 12400 | 50386 |
| q3 | 82,3 | 134,4 | 217,0 | 434,3 |

Unbounded VOLL

# 6. Conclusion and discussion

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**Modeling related**

- Capturing the value of flexibility involves considering an integrated framework ("multiple asset") under long time horizons with adequate granularity.

- The total cost minimization approach adopted is the best way of obtaining an optimal mix integrating short, mid and long-term requirements.

- Flexibility valuation is highly dependent on model formulation.

- Novel flexible assets (EES and DSM) are highly path dependents (similar to reservoir hydro) thus, they should be stochastically scheduled in order to maximize their value.

- The resulting optimal capacity and energy mix can be seem as a long term benchmark for market design (greenfield hypothesis).

# 6. Conclusion and discussion

## Experiment related

- Including flexibility needs and reliability requirements is mandatory for capacity planning when considering highly variable sources (I-RES).
- EES and DSM enhances the capacity value of I-RES, thus allow to more efficiently accommodate I-RES.
- The high EES investment costs considered impedes its deployment in face to the DSM. Nevertheless EES for primary control (FCR not included in the study) applications could be economically feasible.
- When significant shares of I-RES are forced on the system there is an increasing need for flexibility and operating reserve (aFRR and mFRR) supply.
- The later causes the optimal mix to rapidly switch to a more flexible power system, dislocating base load and mid-load technologies progressively.
- System cost rises quadratically, and electricity prices and price volatility rises exponentially subject to the forced increase of RE shares.

# 6. Conclusion and discussion

**Remarks:**

## Modeling related

- Could operating reserve cost be co-optimized within the model?
- Further modules should be done to integrate interconnections in the study.
- The greenfield hypothesis can be enhanced to a brownfield framework in which investment/retirement decisions could be represented to model systems in transition.

## Experiment related

- Further test should be done comprising:
  - Minimum power restrictions of conventionals
  - cost dependent DSM levels
  - Novel highly flexible conventional technologies
  - EES investment cost sensitivities
  - I-RES doldrums
  - Fuel and CO2 prices

*Thank you for your attention.*

*Any questions?*

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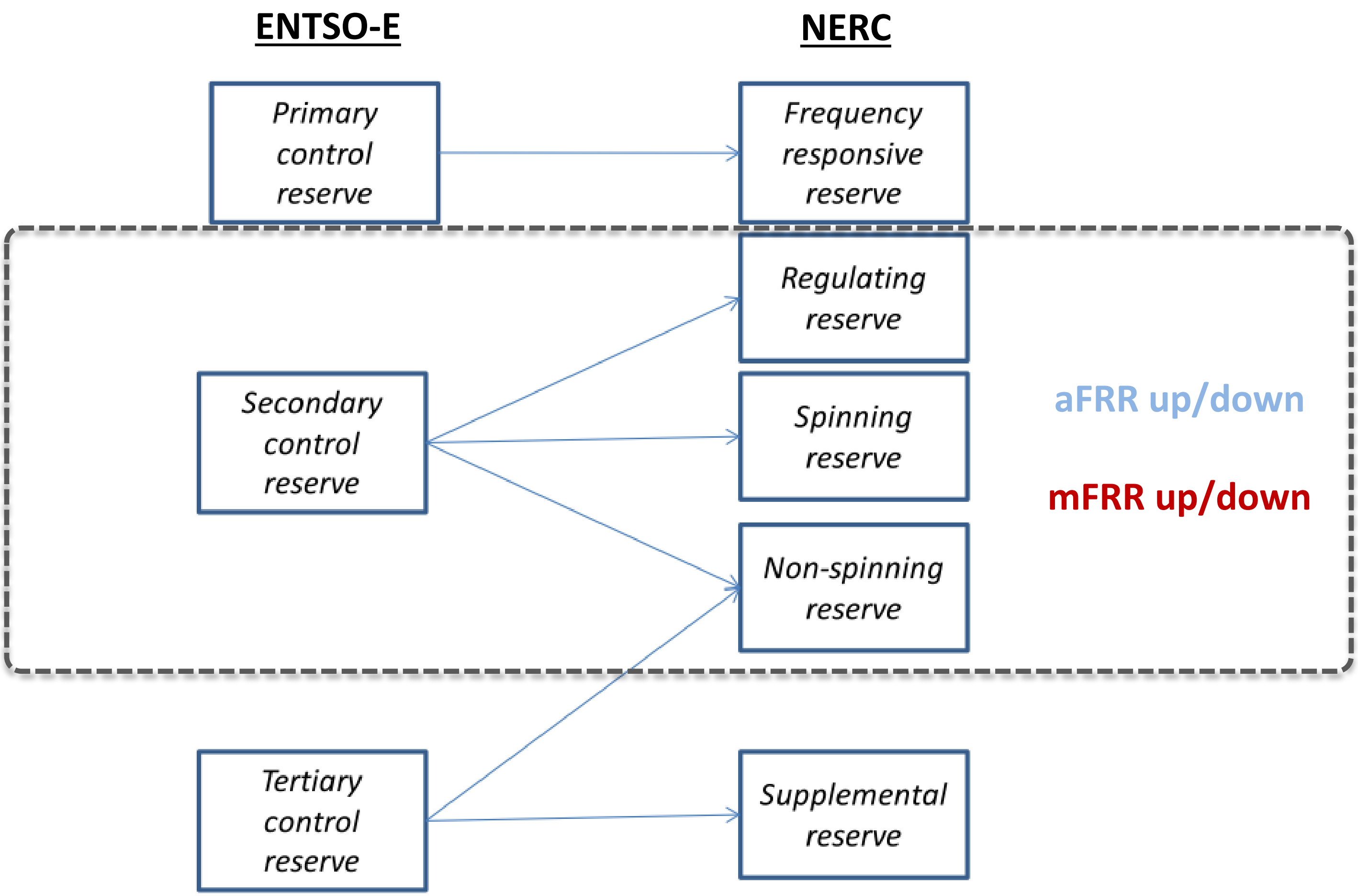
# APPENDIX

# 4. Model presentation




Source: NREL 2011, “Operating Reserves and Variable Generation”

# 4. Model presentation

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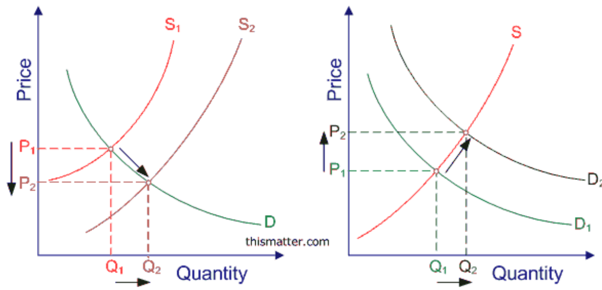
## Multiple services over the entire time horizon

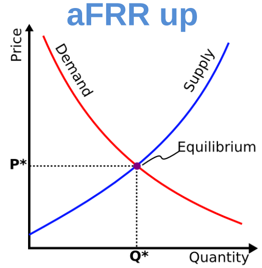
### Energy balancing: J-1 market



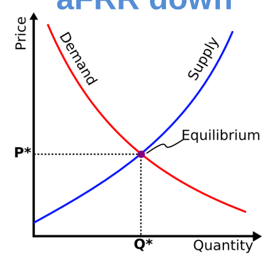

MT

### Secondary control

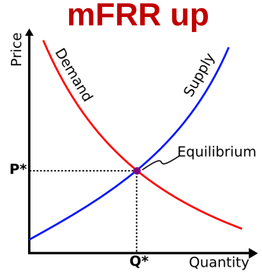
**aFRR up**



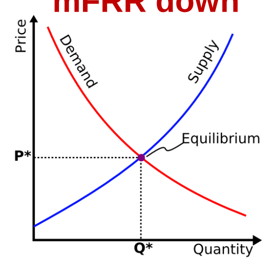

**aFRR down**




**mFRR up**




**mFRR down**

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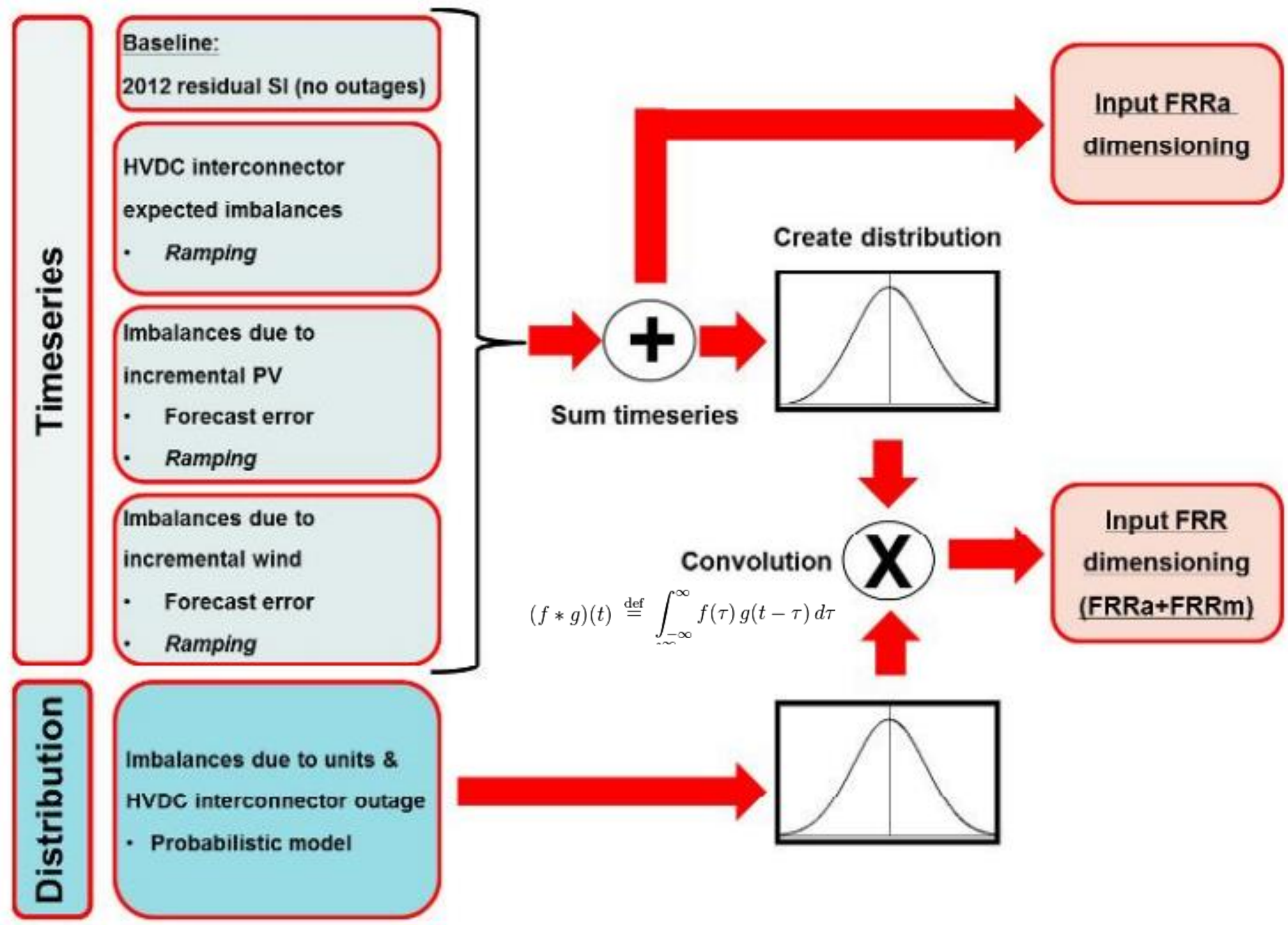
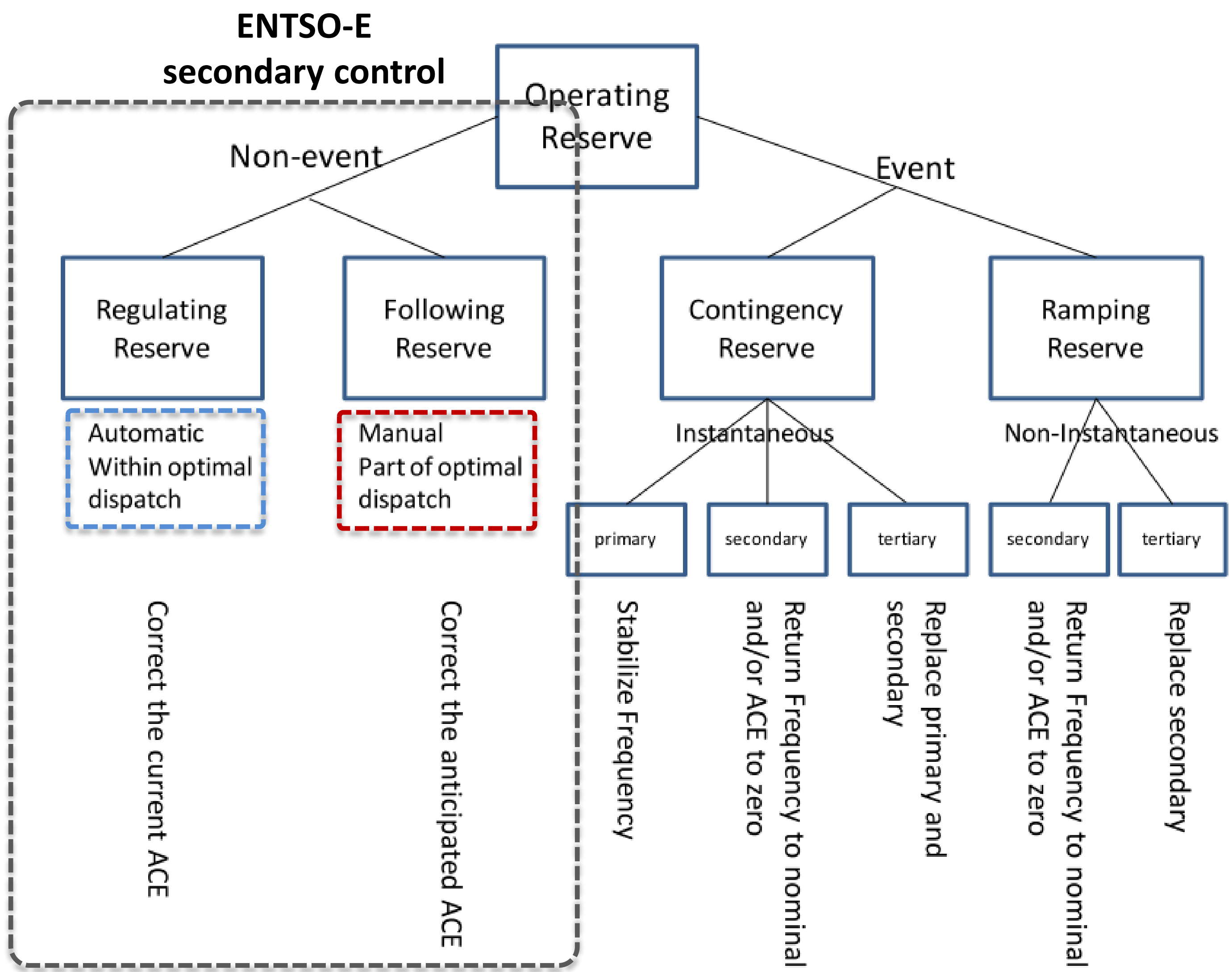
# 4. Model presentation




Source: ELIA, 2012.

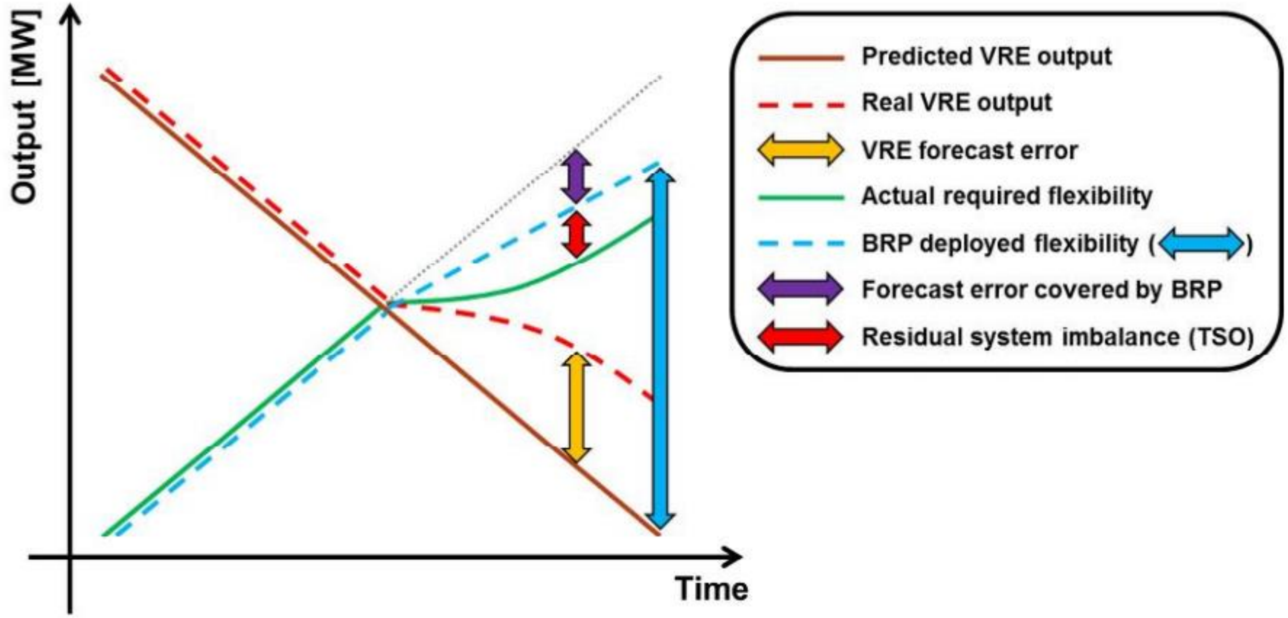
# 4. Model presentation



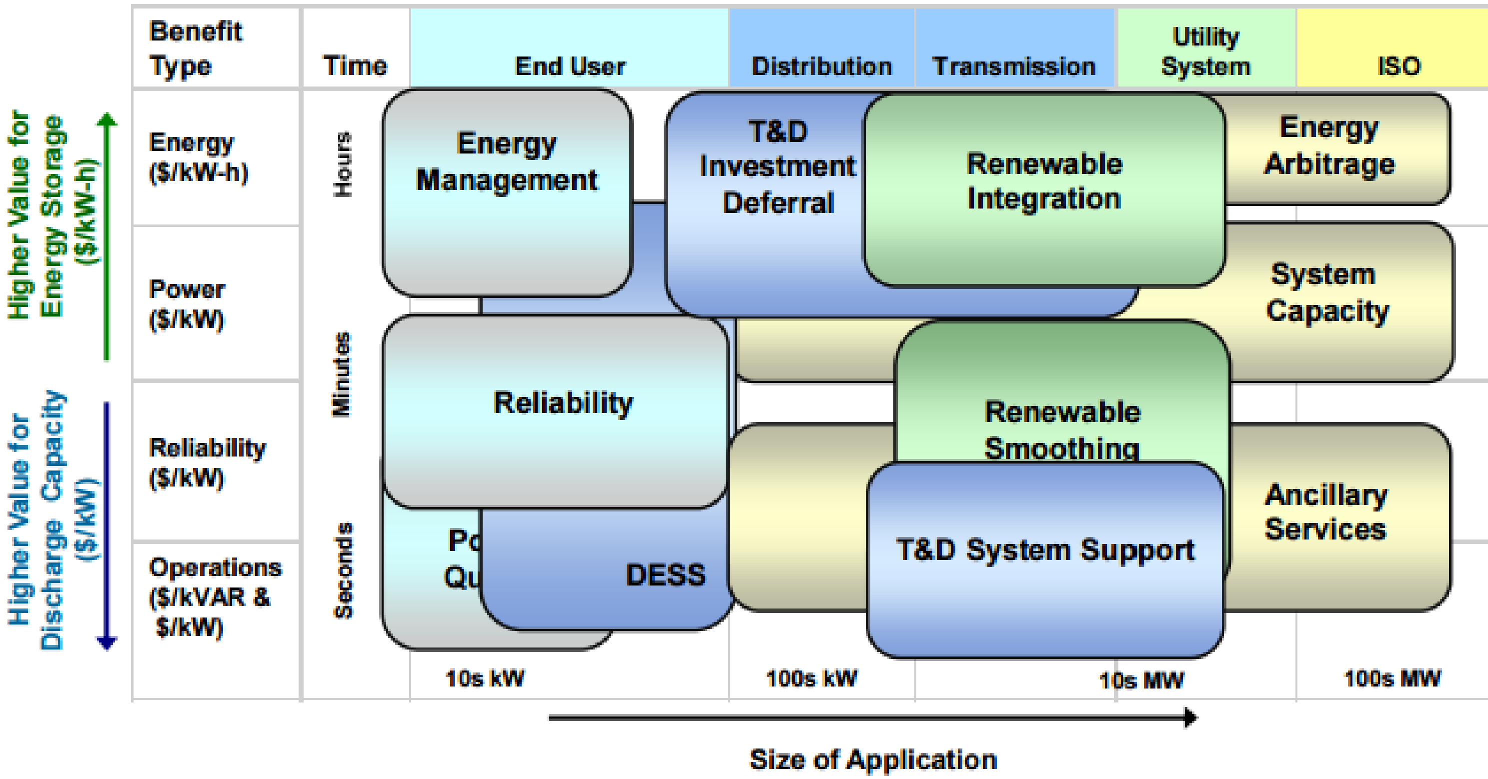

Source: NREL 2011, “Operating Reserves and Variable Generation”

# 4. Model presentation

How will be covered this the gap? By who?

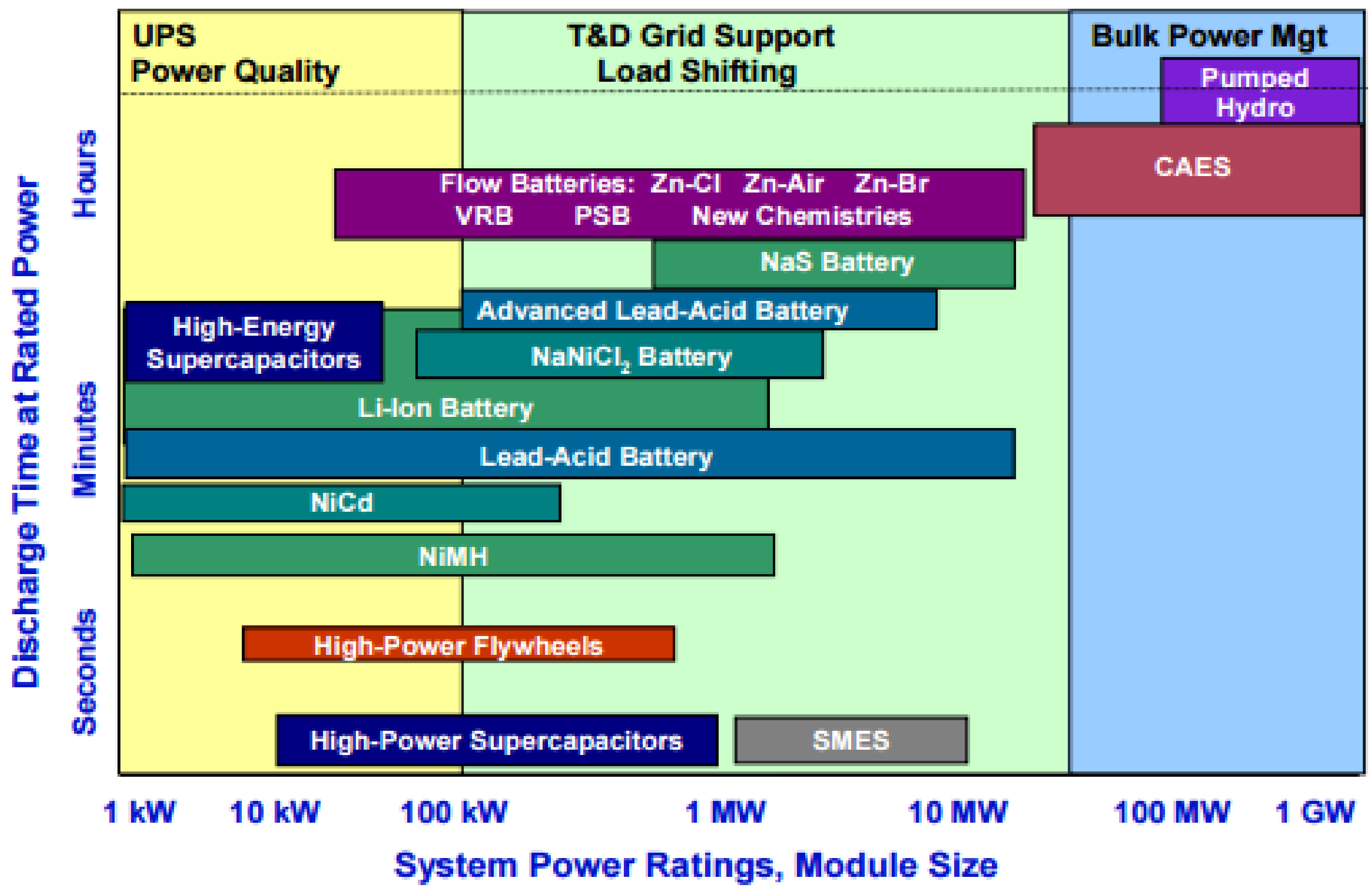



Source: ELIA, 2012.




**Operational Benefits Monetizing the Value of Energy Storage. Source: EPRI 2010.**

## EES technologies: Which ones and what for?




**Positioning of Energy Storage Technologies. Source : EPRI 2010.**