TECHNICAL AND ECONOMIC ANALYSIS OF THE EUROPEAN ELECTRICITY SYSTEM WITH 60% RES
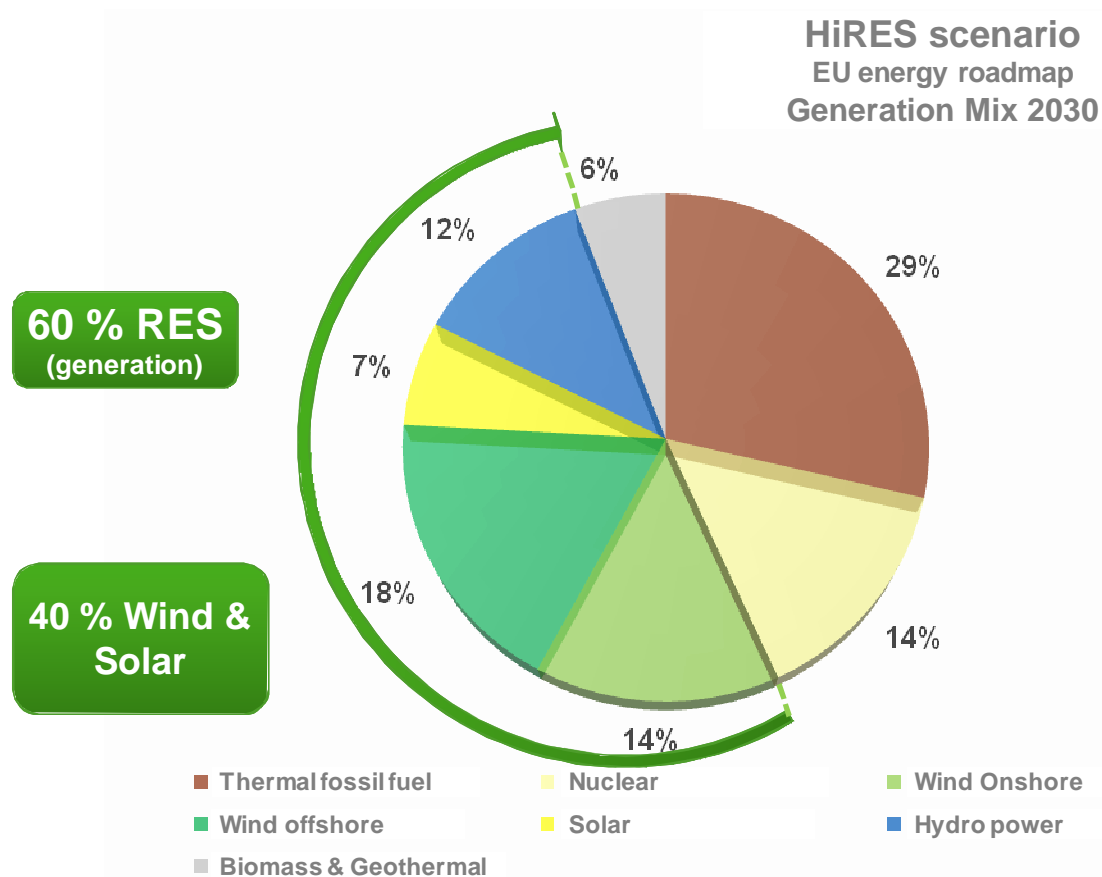
Alain Burtin

EDF R&D

Paris, 12 avril 2016

# Simulation of the EU Energy Roadmap « HiRES 2030 » scenario

HiRES scenario
EU energy roadmap
Generation Mix 2030

60 % RES (generation)

40 % Wind & Solar

29%

14%

14%

18%

7%

12%

6%

- ■ Thermal fossil fuel
- ■ Wind offshore
- ■ Biomass & Geothermal
- ■ Nuclear
- ■ Solar
- ■ Wind Onshore
- ■ Hydro power

High RES 2030	GW	Load factor (h/yr)
Solar (PV)	220	1100
Onshore wind	280	1900
Offshore wind	205	3200
Hydro	120	3800

Fuel	Price
Coal	86 €/t
Gas	10 €/MMBtu
Oil	107 €/baril
CO_2	35 €/t

What is this study about?
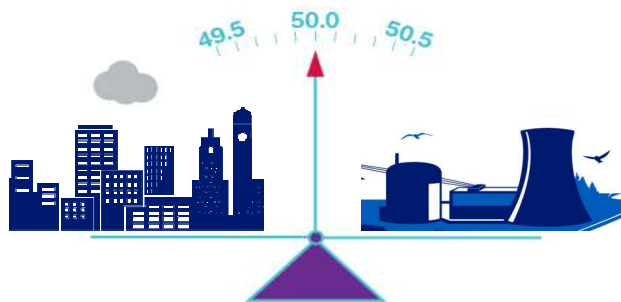
Connecting RES and load

PV   Wind   Hydro
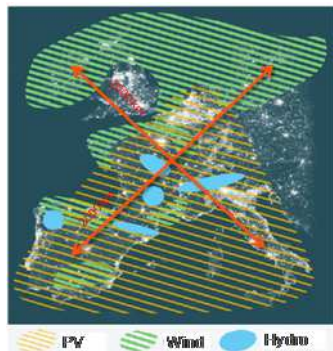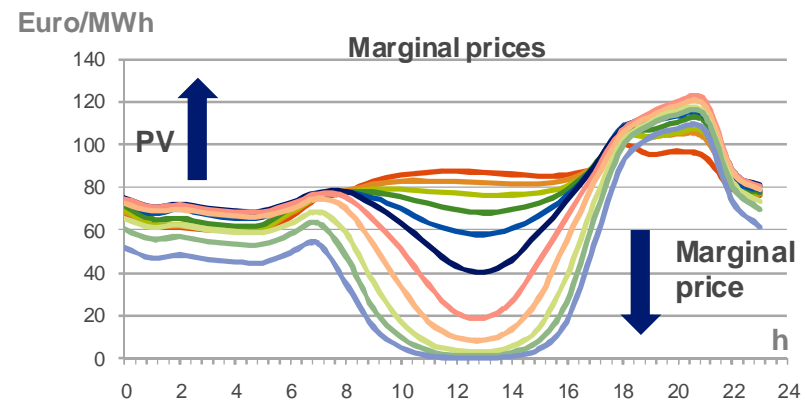
Flexibility to handle variability
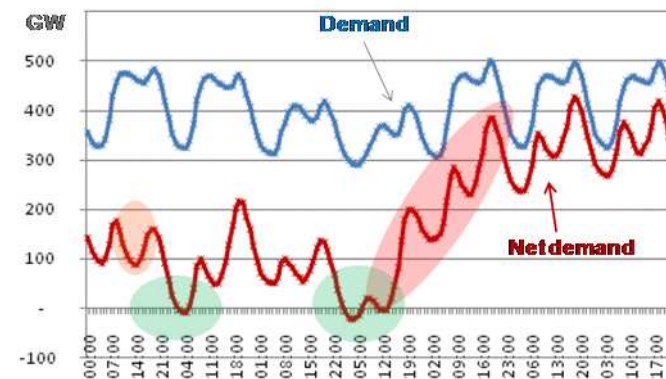
Keeping the lights on

Balancing the economics

And the good news are…

The lights will stay on so no emerging market for candles!

That said …

Geographical diversity does help, but there is still significant variability at European level

Integrating a large share of variable RES requires a coordinated development of RES and networks

Variable RES are key to the decarbonisation of electricity production but the system still needs backup capacity for security of supply

Not only conventional generation, but also variable RES, will contribute to balancing and ancillary services
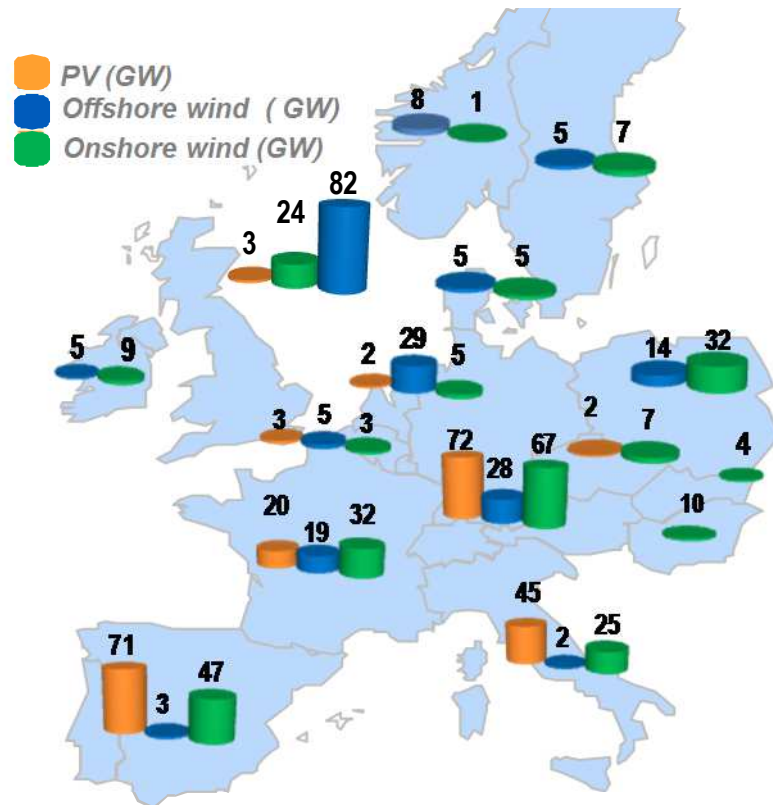
Storage and active demand may to a certain extent supplement generation to balance supply and demand

Variable RES production should potentially provide new services like fast frequency response (inertia)

The pace of deployment of RES should be optimised in order to limit costs of storage or excessive curtailment

Integrating a large share of variable RES requires a coordinated development of RES and networks

RES geographical distribution

PV (GW)
Offshore wind (GW)
Onshore wind (GW)

Network development scenario

TYNDP 2014
+47 GW en 16 ans
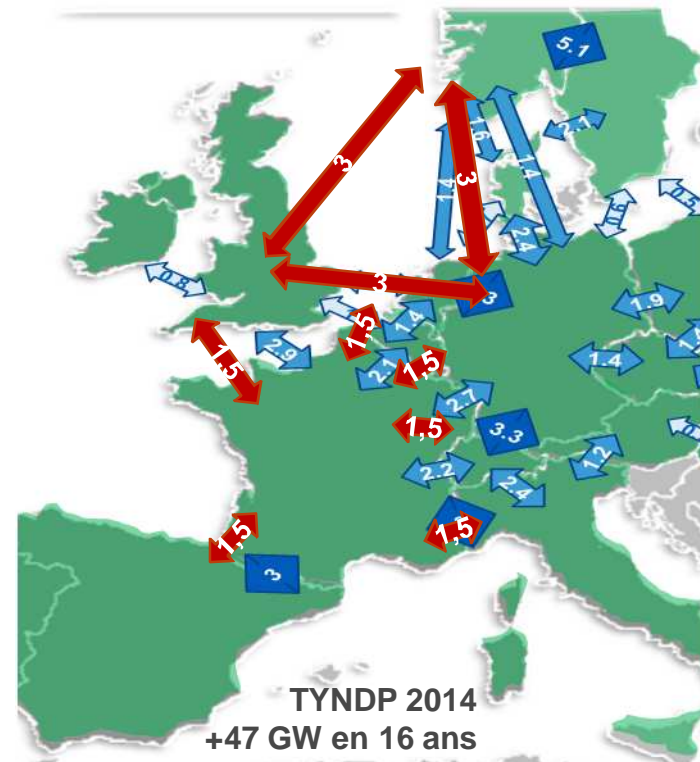
Interconnection reinforcement (GW) similar to TYNDP 2014

Interconnection reinforcement TYNDP 2010 (GW)

Geographical diversity does help, but there is still significant variability at European level

Wind onshore generation for different geographical areas

Load factor

Source RTE

Day

| France | Brittany | Farm |

Installed power : 280 GW

Onshore wind daily average generation 30 climatic years

Average load factor : 25%

250
200
150
100
50
-

Winter

Summer

15%

30%

Average difference of daily generation: 90 GW

0   30   60   90   120   150   180   210   240   270   300   330   360
JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
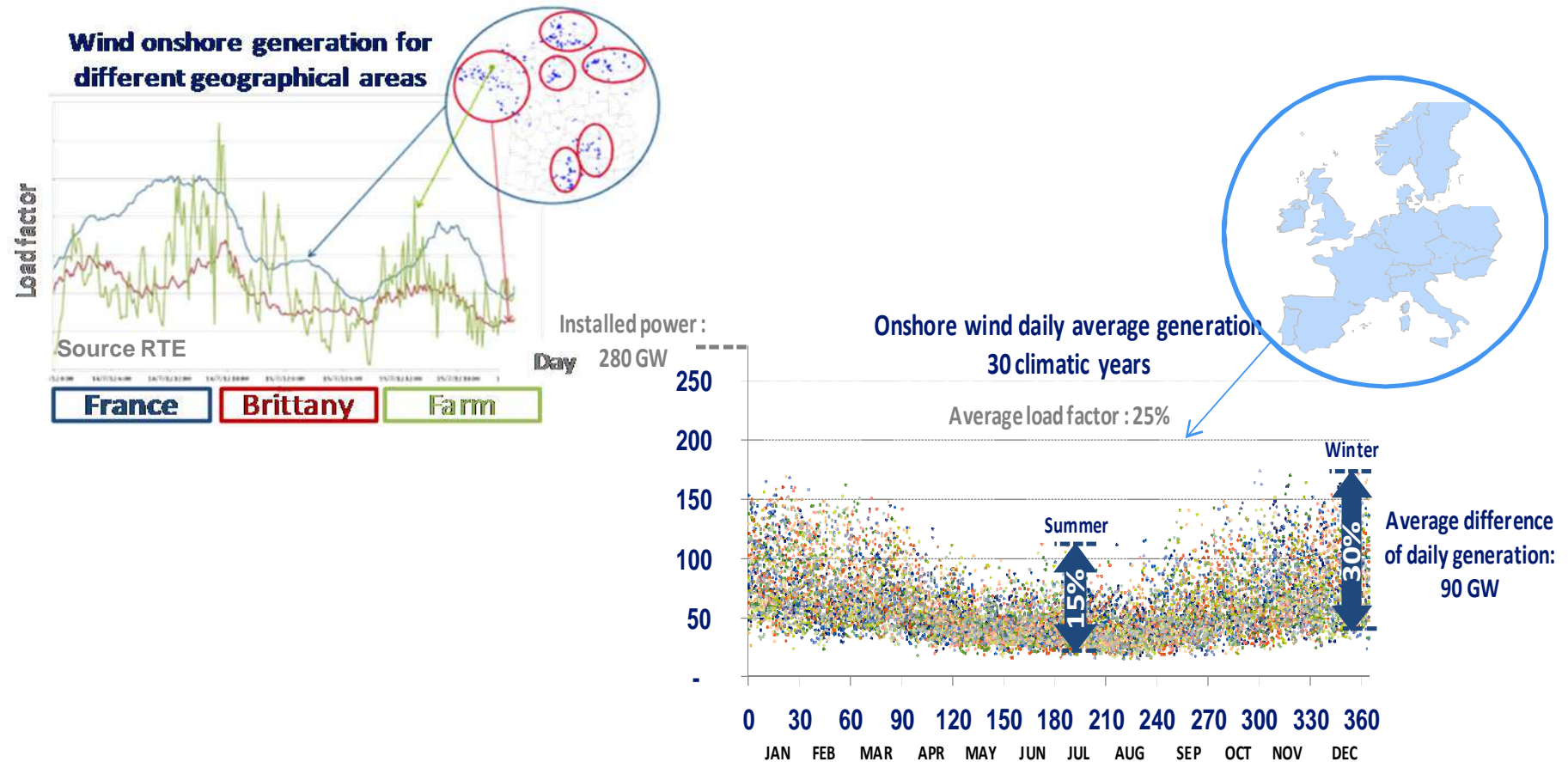
You can reduce the variability of wind and PV at local level but the correlation in wind regimes acts as a limit at continental level

Not only conventional generation, but also variable RES, will contribute to balancing and ancillary services

GW — **European Demand**

500
400
300
200
100
-
-100

Middle of the day valley

Net demand (demand – variable RES)

00:00 07:00 14:00 21:00 04:00 11:00 18:00 01:00 08:00 15:00 22:00 05:00 12:00 19:00 02:00 09:00 16:00 23:00 06:00 13:00 20:00 03:00 10:00 17:00

Penetration of RES > 100 %

400 GW ramp between Sunday and Monday

RES need to provide downward flexibility as well as ancillary services
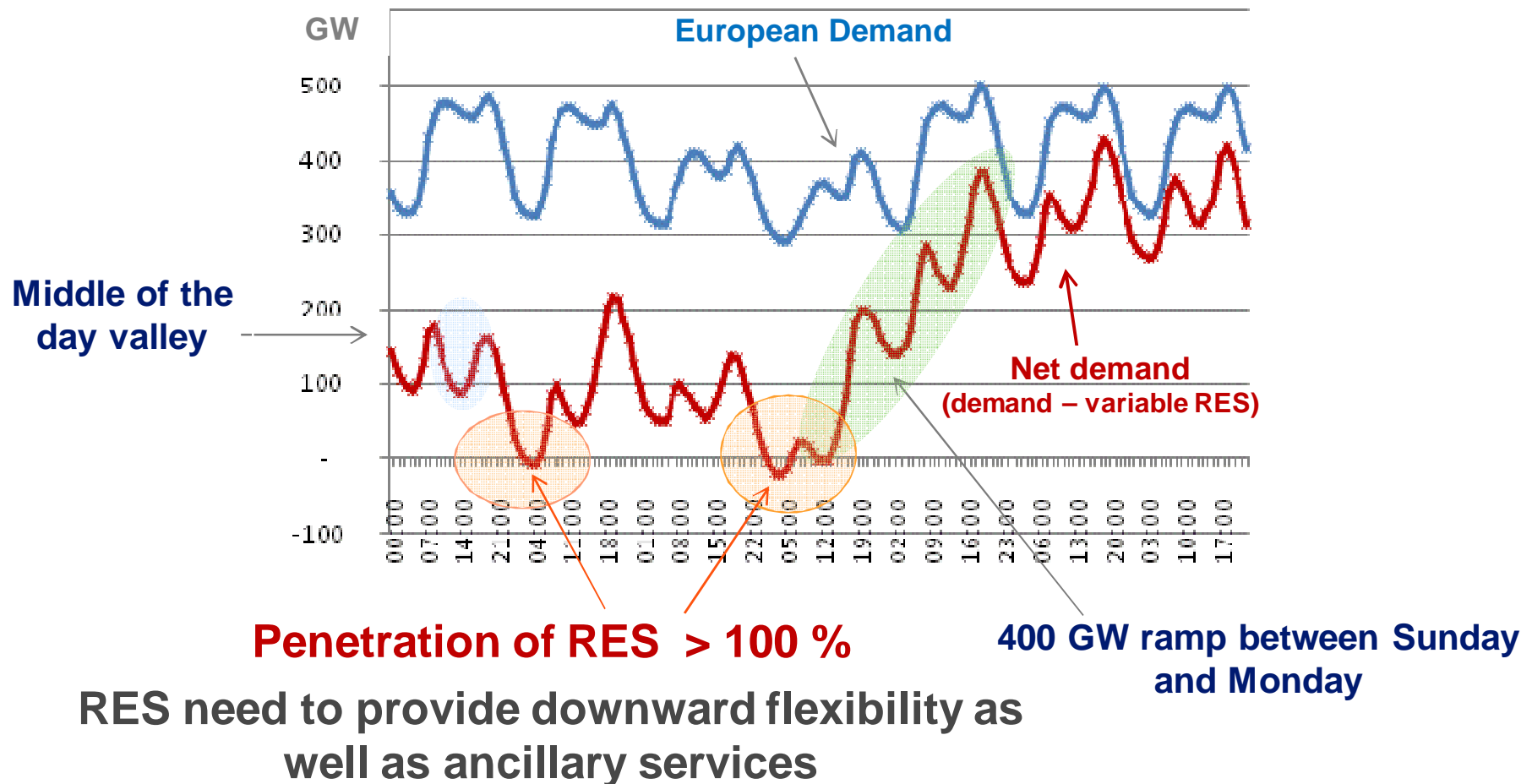
Storage and active demand may to a certain extent supplement generation to balance supply and demand

Net benefit of storage for different countries

M€/y

Weekly storage (40 h)

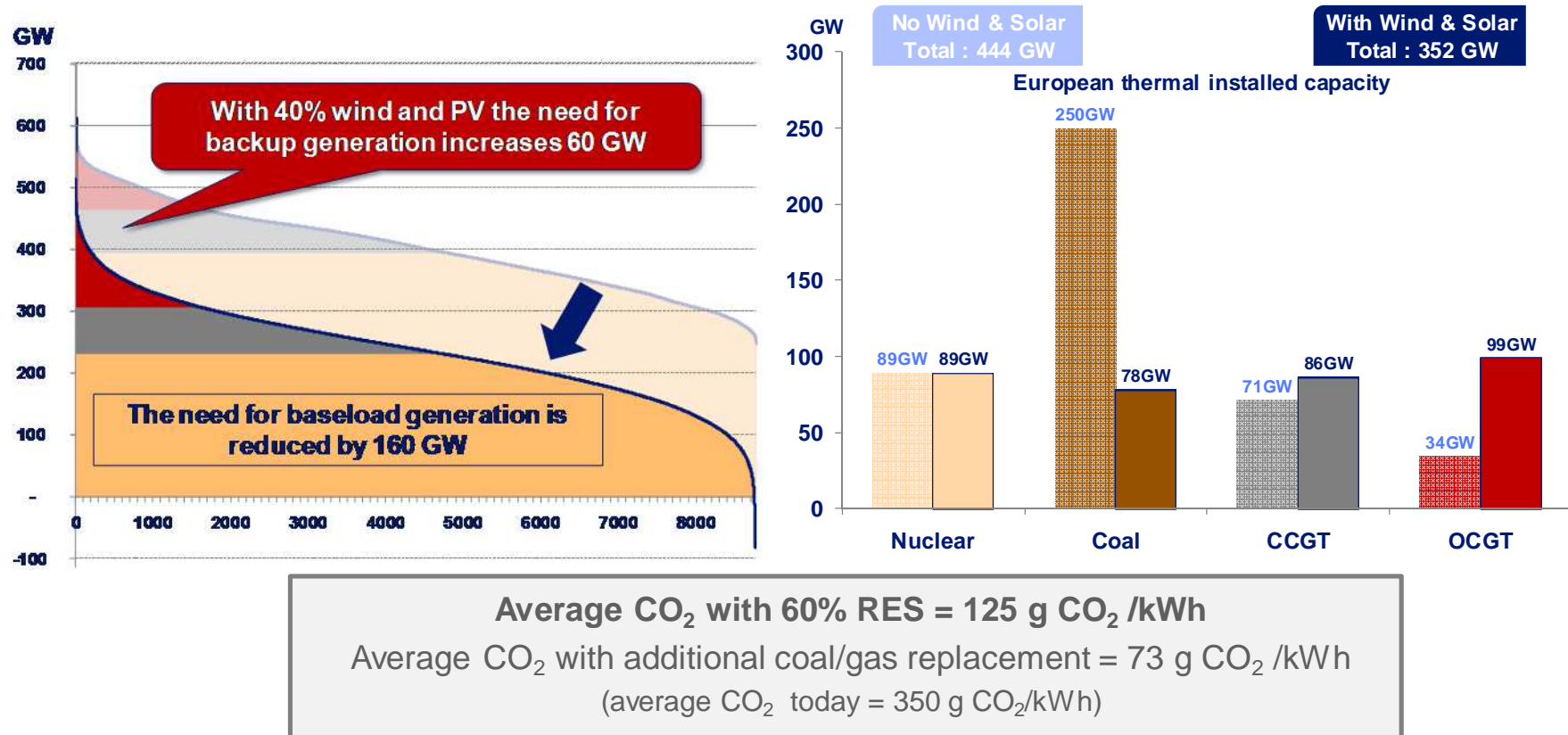France   Germany + Austria   UK

1 GW   2 GW   4 GW   1 GW   2 GW   4 GW   1 GW   2 GW   4 GW
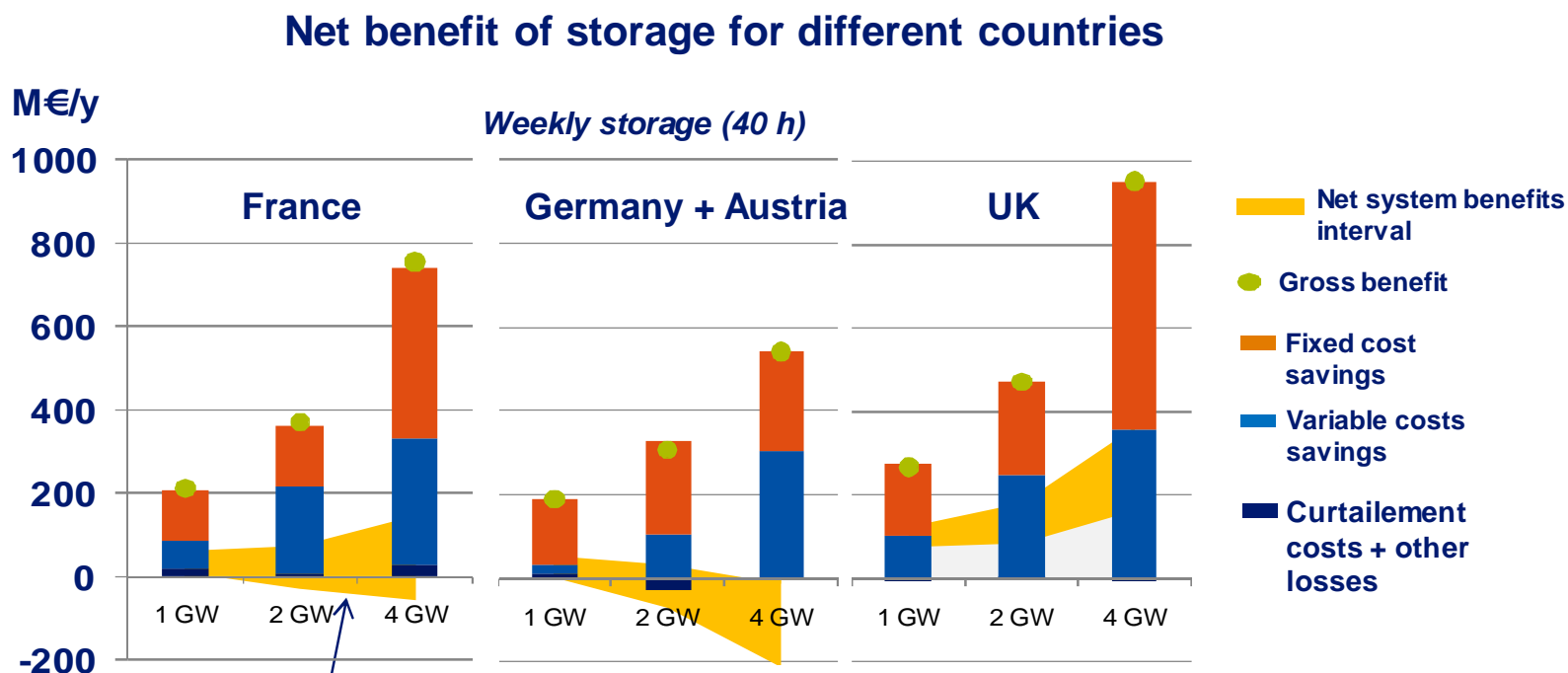
Net benefit interval as a function of storage cost and installed capacity

Legend:
- Net system benefits interval
- Gross benefit
- Fixed cost savings
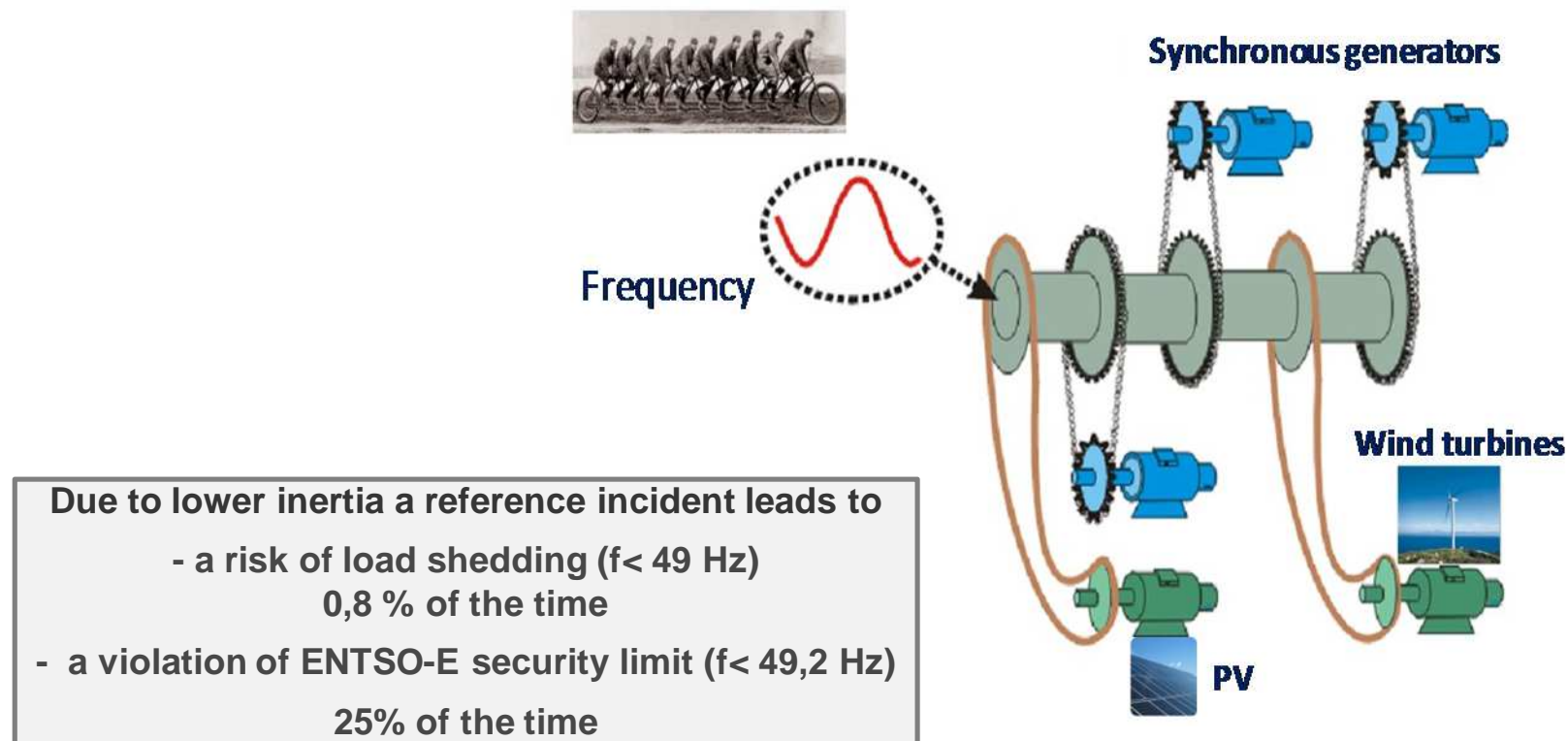- Variable costs savings
- Curtailement costs + other losses

Storage and flexible demand contribute to the flexibility required for balancing but do not replace the need for backup generation

Variable RES are key to the decarbonisation of electricity generation but the system still needs backup capacity for security of supply

With 40% wind and PV the need for backup generation increases 60 GW

The need for baseload generation is reduced by 160 GW

GW
700
600
500
400
300
200
100
-
-100

0 1000 2000 3000 4000 5000 6000 7000 8000

No Wind & Solar Total : 444 GW

With Wind & Solar Total : 352 GW

European thermal installed capacity

GW
300
250
200
150
100
50
0

250GW

89GW 89GW

78GW

71GW 86GW

34GW 99GW

Nuclear   Coal   CCGT   OCGT

Average CO$_2$ with 60% RES = 125 g CO$_2$ /kWh

Average CO$_2$ with additional coal/gas replacement = 73 g CO$_2$ /kWh

(average CO$_2$ today = 350 g CO$_2$/kWh)

Full decarbonisation can only be achieved with a significant share of carbon free base load, such as nuclear

# Variable RES production should potentially provide new services like fast frequency response

Due to lower inertia a reference incident leads to

- a risk of load shedding (f< 49 Hz)
0,8 % of the time

- a violation of ENTSO-E security limit (f< 49,2 Hz)

25% of the time

Curtailment to avoid stability problems during critical periods can only be limited if variable RES have the technical capability to provide fast frequency response (synthetic inertia)

The pace of deployment of RES should be optimised in order to limit costs of storage or excessive curtailment

VRE value in comparison to base price per country
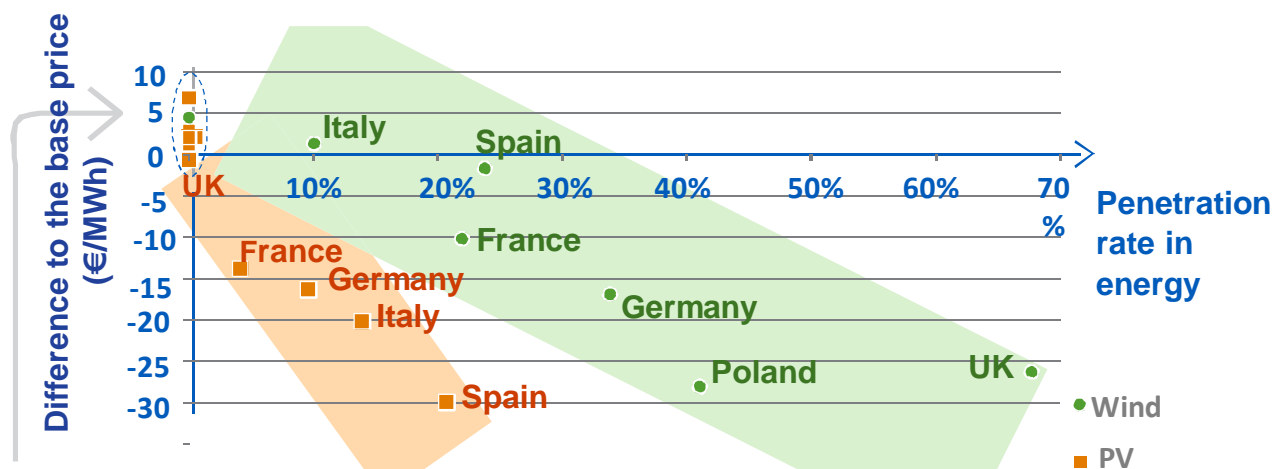
With ~0% RES, the first MWs of RES have a value close to the base price

The system value of variable RES will decrease as their penetration levels increases and this is more pronounced for PV

Geographical diversity does help, but there is still significant variability at European level

Integrating a large share of variable RES requires a coordinated development of RES and networks

Variable RES are key to the decarbonisation of electricity production but the system still needs backup capacity for security of supply

Not only conventional generation, but also variable RES, will contribute to balancing and ancillary services

Storage and active demand may to a certain extent supplement generation to balance supply and demand

Variable RES production should potentially provide new services like fast frequency response (inertia)

The pace of deployment of RES should be optimised in order to limit costs of storage or excessive curtailment

METHODOLOGY FOR THE ANALYSIS OF THE EUROPEAN SYSTEM WITH HIGH RES SCENARIOS

Vera Silva

EDF R&D

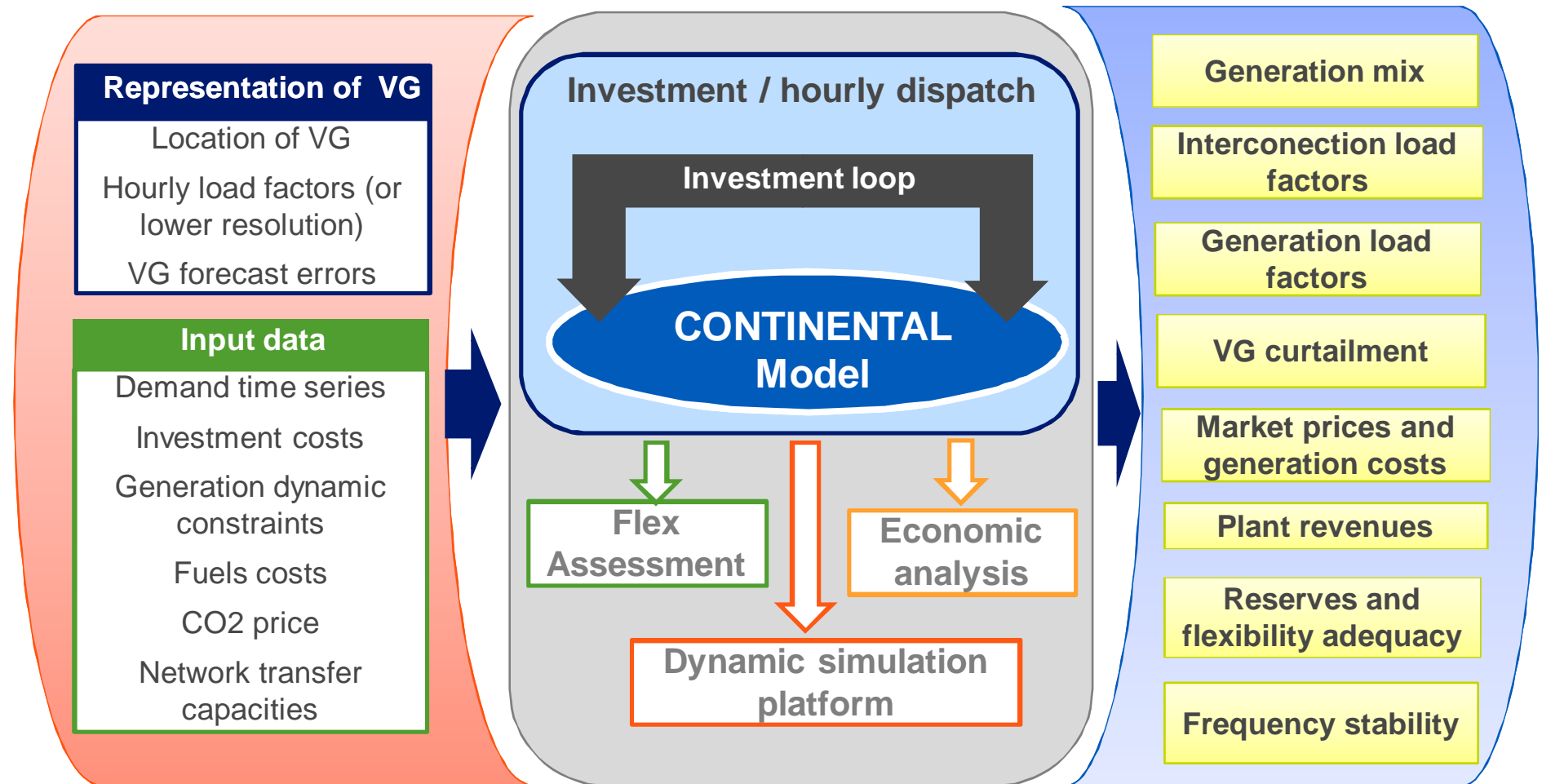# Modeling the European interconnected system is a challenging task

In order to represent a "realistic" European system, models should include:

- description of different countries generation mix with units technical constraints and key transmission corridors with more or less details depending on their size

- interconnection capacities between countries

- management of water reservoirs and pump storage

- demand and VG stochastic behavior across the European system => *time-synchronise* data with hourly (or lower) resolution and over a large number of climate years

Some key challenges of this problem:

- **Hydro** and **storage** flexibility play a key role in the integration of variable generation but its optimization is **a computationally heavy stochastic problem**

- **Generation scheduling** needs to be **performed across the whole Europe** including **interconnection** and key transmission constraints => **problem size**

- **Impact of variable generation on short term risks and dynamic stability** is essential for scenarios with high penetrations of VG => **analysis of system operation needed**

An integrated approach for the technical and economical analysis of High RES scenarios in Europe is required

Representation of VG
- Location of VG
- Hourly load factors (or lower resolution)
- VG forecast errors

Input data
- Demand time series
- Investment costs
- Generation dynamic constraints
- Fuels costs
- CO_2 price
- Network transfer capacities

Investment / hourly dispatch

Investment loop

CONTINENTAL Model

Flex Assessment

Economic analysis

Dynamic simulation platform

- Generation mix
- Interconection load factors
- Generation load factors
- VG curtailment
- Market prices and generation costs
- Plant revenues
- Reserves and flexibility adequacy
- Frequency stability

Reference : M. Lopez-Botet, et all, *'Methodology for the economic and technical analysis of the European power system with a large share of variable renewable generation'*, presented at **IEEE PES General Meeting**, Washington, USA, 27-31 July, 2014.

Generation investment Model for interconnected systems including flexibility constraints

The objective is to obtain the thermal generation mix that ensures that for every new unit the revenues equals its annuitized fixed costs :

☐ Fixed costs include investment and O&M

☐ Variable costs include start-up and fuel costs

**The generation mix is optimized in two iterative steps:**

☐ Load duration curve based heuristic to propose a candidate solution

☐ Validation of the heuristic solution solving the hourly load-generation dispatch => creates an marginal cost signal that feeds the investment loop

The generation mix needs to respect an adequacy criterion

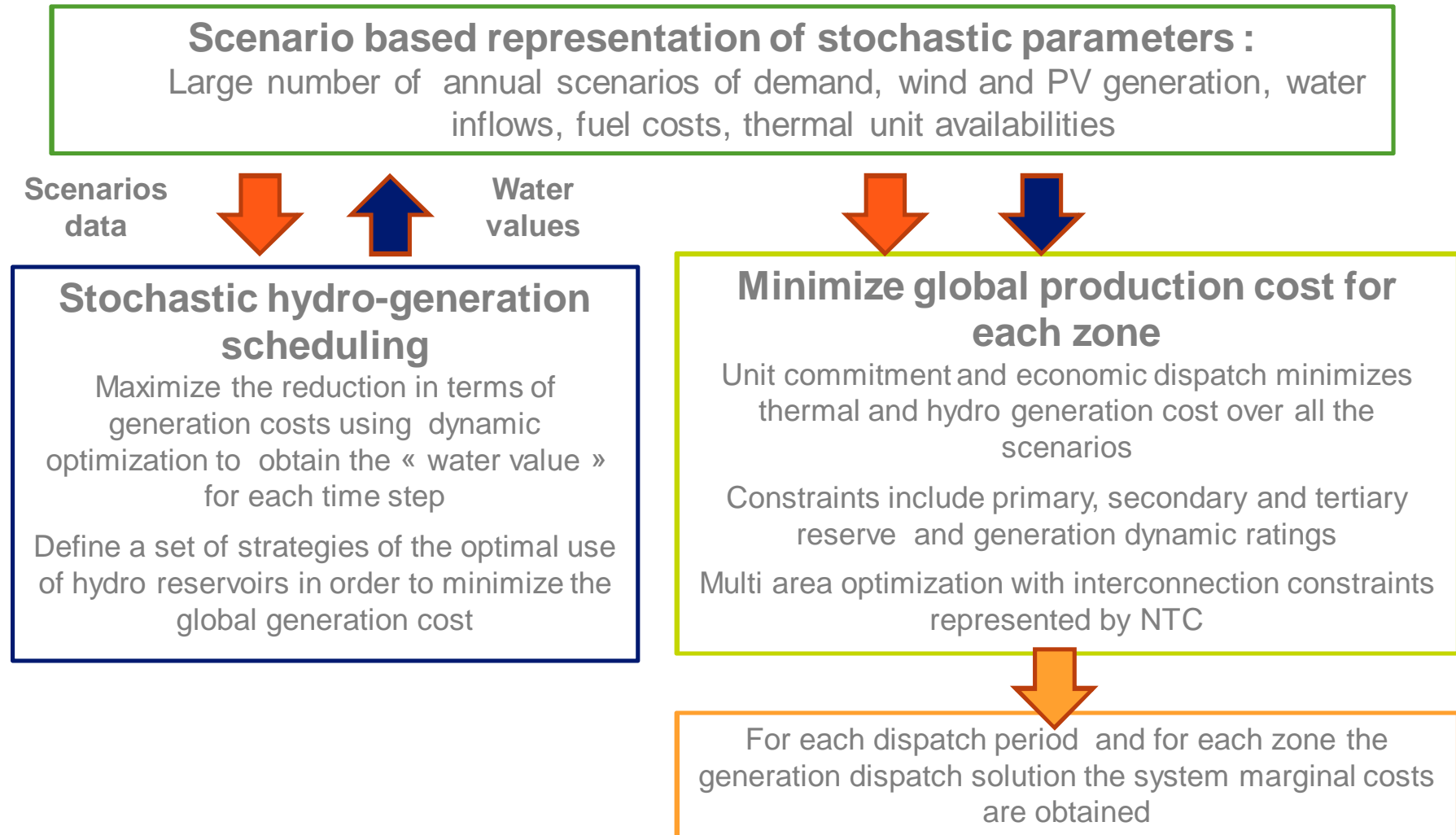- 3h/year with marginal price = VOLL

INPUT DATA

Demand	Storage
Variable generation profiles	Investment costs
	Commodity prices
Interconnection constraints	CO_2 price

Investment loop
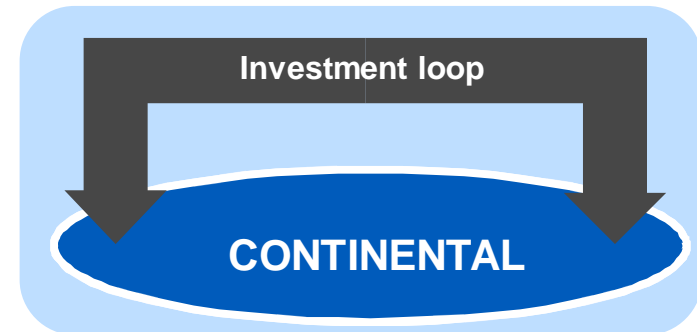
CONTINENTAL

OUTPUT

Optimal thermal	Market clearing prices
generation mix	CO_2 emissions
Production dispatch	Hydro stock level paths
Production costs	Interconnection uses

Continental Model for hydro-thermal hourly unit commitment and dispatch

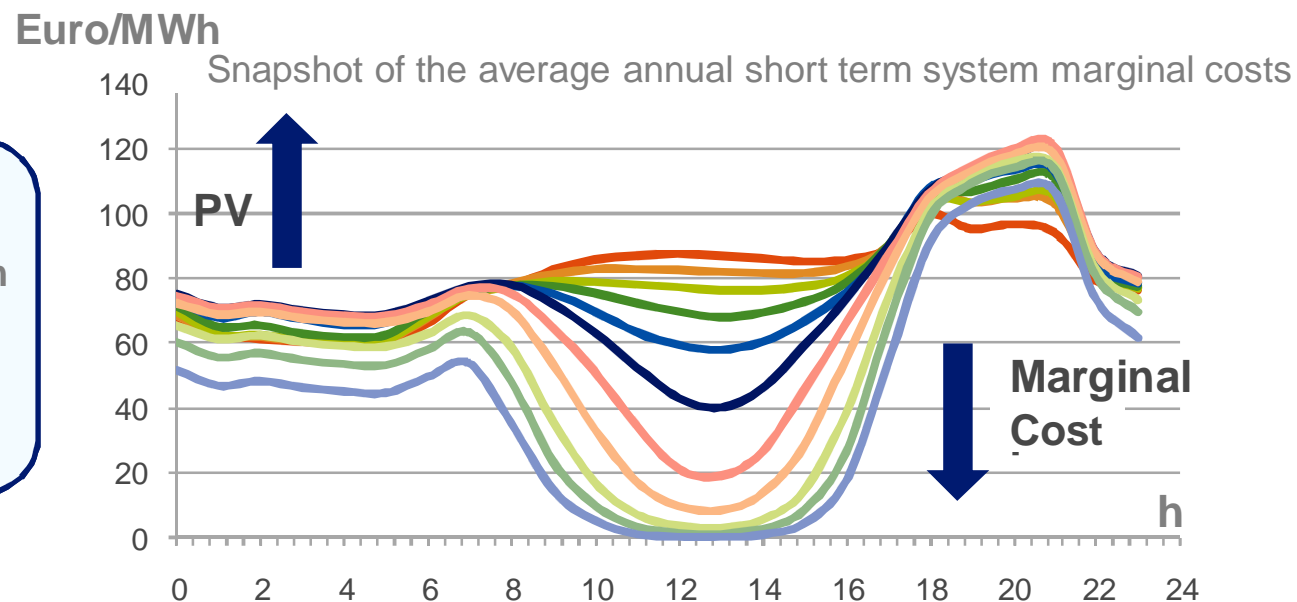**Scenario based representation of stochastic parameters :**
Large number of annual scenarios of demand, wind and PV generation, water inflows, fuel costs, thermal unit availabilities

Scenarios data

Water values

Stochastic hydro-generation scheduling

Maximize the reduction in terms of generation costs using dynamic optimization to obtain the « water value » for each time step

Define a set of strategies of the optimal use of hydro reservoirs in order to minimize the global generation cost

Minimize global production cost for each zone

Unit commitment and economic dispatch minimizes thermal and hydro generation cost over all the scenarios

Constraints include primary, secondary and tertiary reserve and generation dynamic ratings

Multi area optimization with interconnection constraints represented by NTC

For each dispatch period and for each zone the generation dispatch solution the system marginal costs are obtained

Reference: Langrene, N., van Ackooij, W., Breant, F., "*Dynamic Constraints for Aggregated Units: Formulation and Application* », **Power Systems, IEEE Transactions on** , vol.26, no.3, Aug. 2011

The economic analyses is based on the marginal costs and unit dispatch obtained from Continental Model

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Balancing the economics

The marginal costs are obtained using a system level approach and considering a perfect market

Euro/MWh

Snapshot of the average annual short term system marginal costs

PV

Marginal Cost

140
120
100
80
60
40
20
0

0   2   4   6   8   10   12   14   16   18   20   22   24

h

Reference: Marie Perrot, Vera Silva ·Timothee Hinchliffe·Paul Fourment, Miguel Lopez-Botet Zulueta, Economic and technical analysis of the European system with high RES scenarios, Tenth Conference on The Economics of Energy and Climate Change, 8–9 septembre, 2015, Toulouse

As the penetration of RES increases the base price falls

Drop in Base Price

Base Price in Germany

83€/MWh: Complete Cost of Coal (Base Generation)

Snapshot of the average of the annual short term system marginal costs

€/MWh (left axis): 0, 10, 20, 30, 40, 50, 60, 70, 80, 90

Number of hours in the year (right axis): 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000

X-axis: 0% PV+E, 8% PV+E, 16% PV+E, 24% PV+E, 32% PV+E, 40% PV+E, 48% PV+E, 56% PV+E, 64% PV+E, 72% PV+E, 80% PV+E

Some hours with price at 0€/MWh

Number of hours where spot price is 0 in Germany

For a high penetration of RES, the notion of "base generation" disappears.

Plants need to recover their costs on fewer hours but remain profitable as long as the marginal price when operating is high enough.

For the scenario studied wind and PV are not able to recover their costs

RES market revenues (€/kW/year) (y-axis)

Costs IEA (WEO 2014)

Categories: Solar, Onshore Wind, Offshore Wind

Legend:
- Germany
- Spain
- France
- GB
- Italy
- Poland
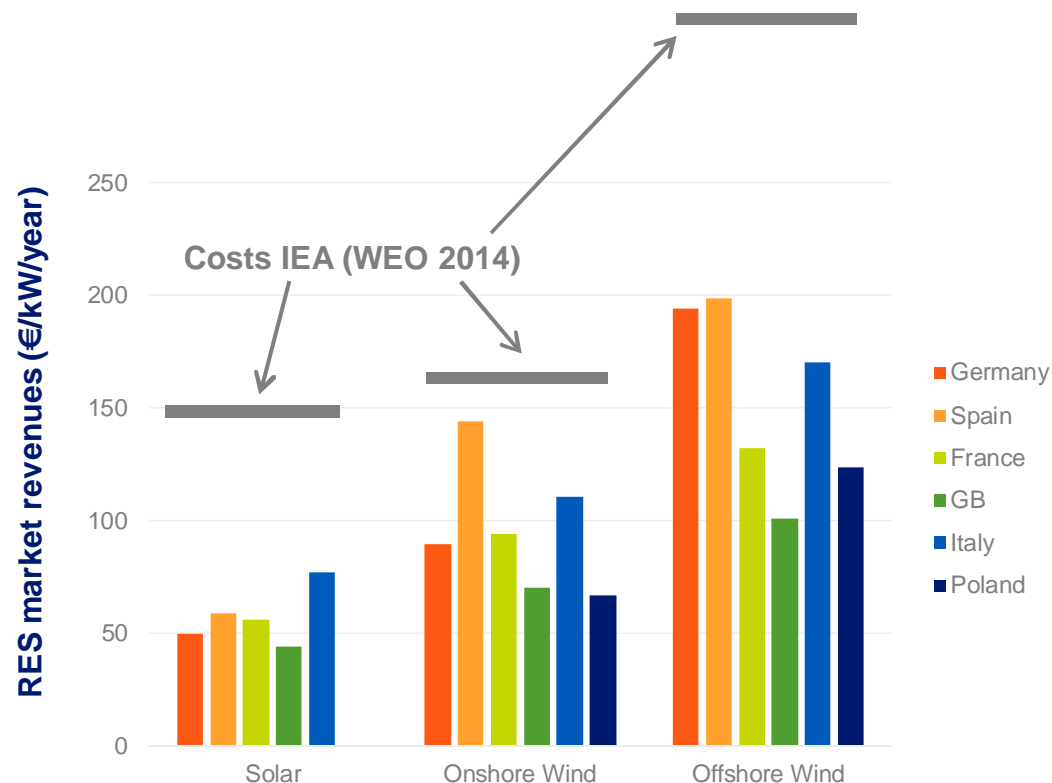
Onshore wind => economic value close to its costs.

Offshore wind => penalised by high investment costs (around 350 €/kW/an)

PV => low revenues of PV due to a pronounced "cannibalisation" effect

eDF | 22   * Includes: investment costs, O&M (labour force, maintenance …) and grid connection costs for offshore wind.

The higher the penetration of RES the lower their value factor. This effect is more pronounced for PV

Sensitivity to variable RES penetration *

60%

RES Penetration

100%, 80%, 60%, 40%, 20%, 0%

V1 V2 V3 V4 V5 REF V6 V7 V8 V9 V10
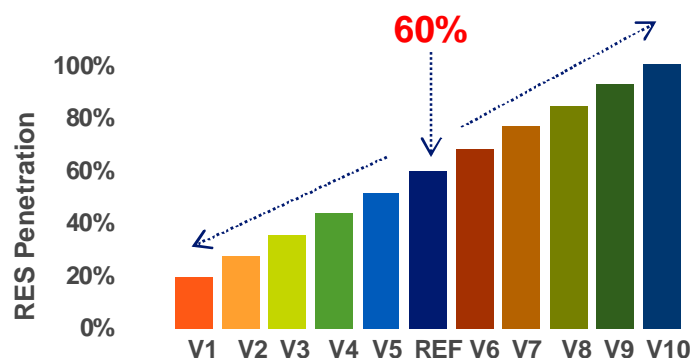
$$\text{Value Factor} = \frac{\text{RES revenue (€/MWh)}}{\text{Base Price(€/MWh)}}$$

Iberian Peninsula

1,2 1,0 0,8 0,6 0,4 0,2 0,0

- PV
- Onshore
- Offshore

7%
6%
2%
23%
21%

ESP - 60% RES

Great-Britain

1,2 1,0 0,8 0,6 0,4 0,2 0,0

0% PV+W, 8% PV+W, 16% PV+W, 24% PV+W, 32% PV+W, 40% PV+W, 48% PV+W, 56% PV+W, 64% PV+W, 72% PV+W, 80% PV+W

- Onshore
- Offshore

5%
63%
13%
1%

GBR - 81% RES

* None of the other parameters, such as the level of interconnection, were modified.
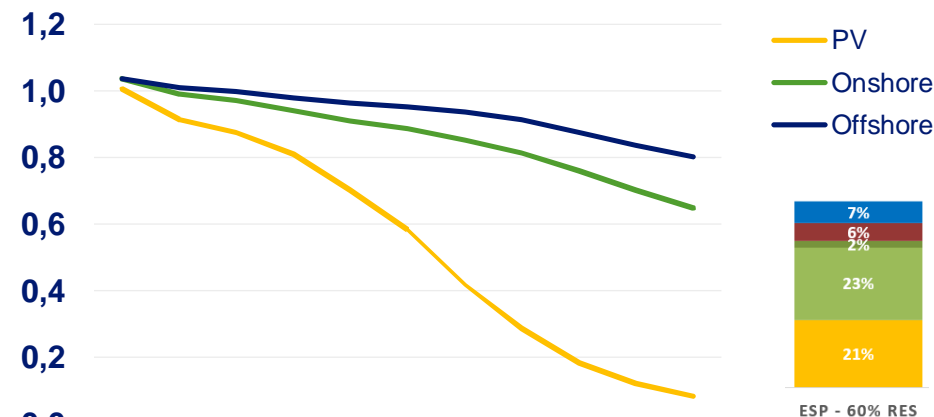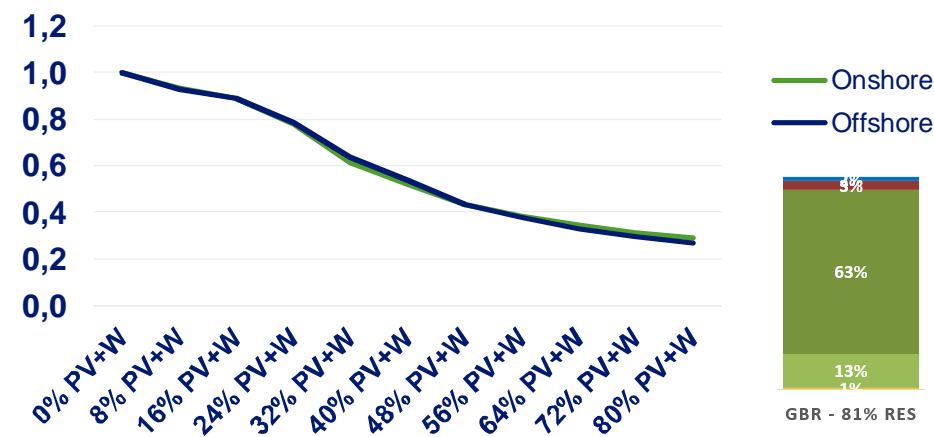
Dedicated tools are used to access the impact of short term uncertainty impact on flexibility and dynamic stability

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- Frequency stability

The exposure of the load-generation balance to weather uncertainties increases significantly

Net demand with 40 % VG wind and solar penetration

Difference between weather years 200 GW (90% of daily net energy demand)
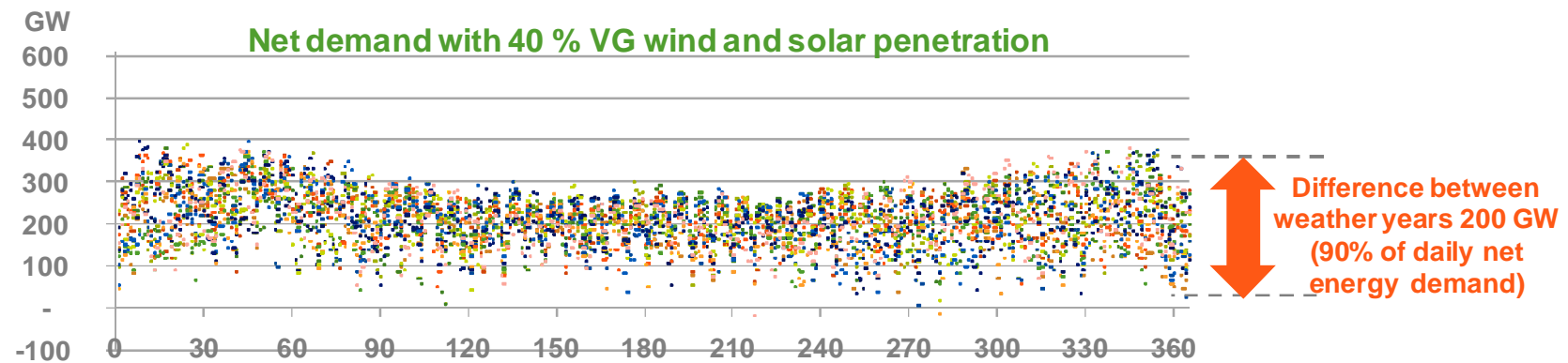
Observability and forecasting are essential to reduce the operation margins required to handle load-generation balancing

PV France   Wind France

MAE (% of installed capacity)

Intra-Day   D+1   D+2   D+3   Statistical

PV Site   Wind Site

Intra-Day   D+1   D+2   D+3
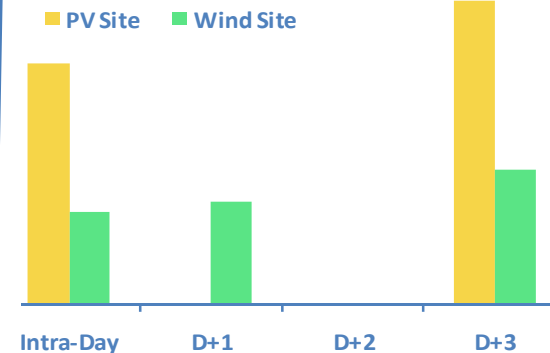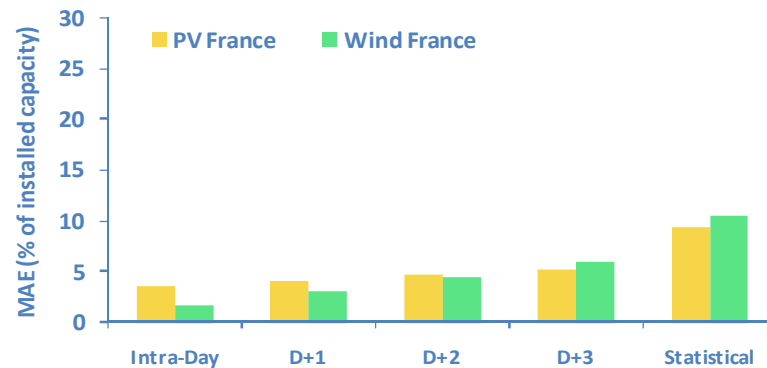
The average mean forecast error at farm level is 2 to 3 times higher than at a country level

We performed a detailed analysis of operation margins and reserves for different countries for the 60% RES scenario

- **An innovative probabilistic approach** was developed to compute operation margins and reserve requirements :

  - Probabilistic models of forecast errors (wind, PV and demand) for each hour and different lead times
  - Probabilistic models of generation availability (considering outages and failure to synchronize)
  - Use of numerical convolution to characterize load-generation balancing distribution

Example of distribution of wind forecast errors
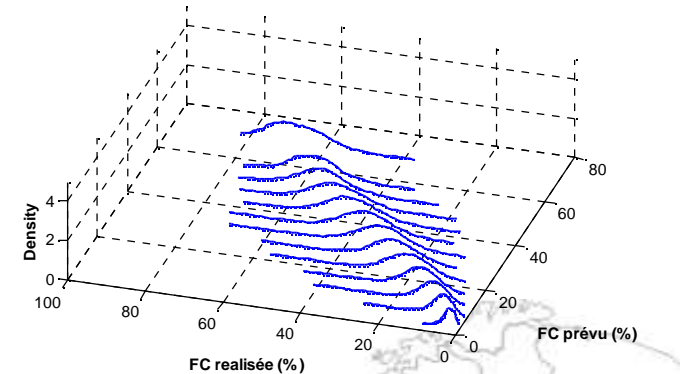
Operation margins and reserves are defined using a risk level of 1 %

Risk level 1%

Upward   Downward

Surplus

Surplus < 0   Surplus > 0

Load – generation balance
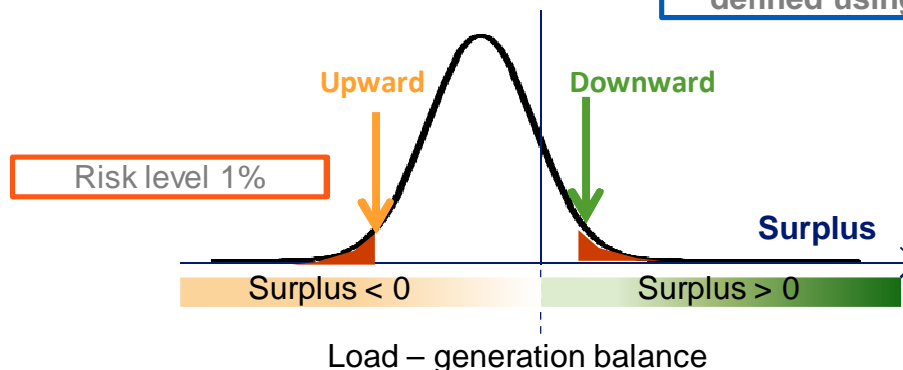
Reference: G. Prime, V. Silva, M. Lopez-Botet Zulueta, **Integration of flexibility assessment to generation planning of large interconnected systems**, **IEEE Transactions on Power Systems** (submitted)
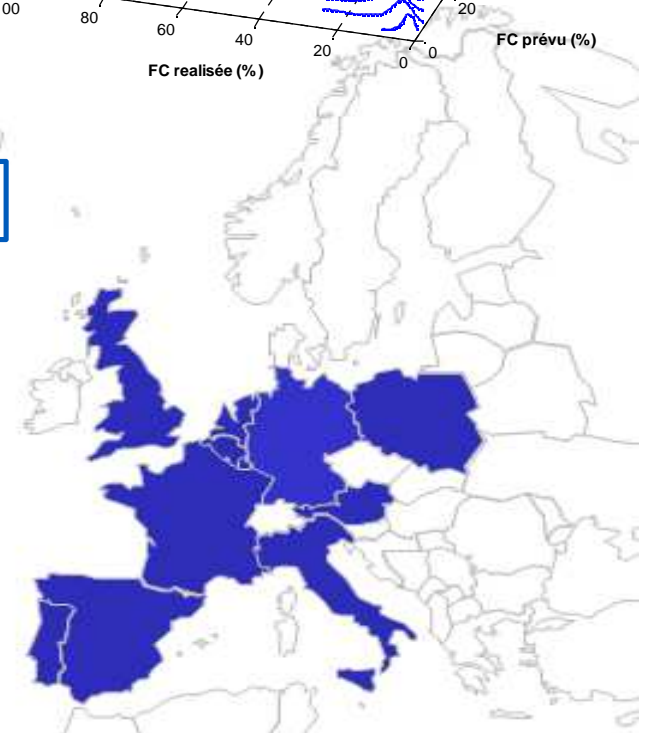
With a high share of variable RES operation margins no longer follow well defined daily and seasonal patterns

Profile of day-ahead upward operation margin required to cover 1% risk
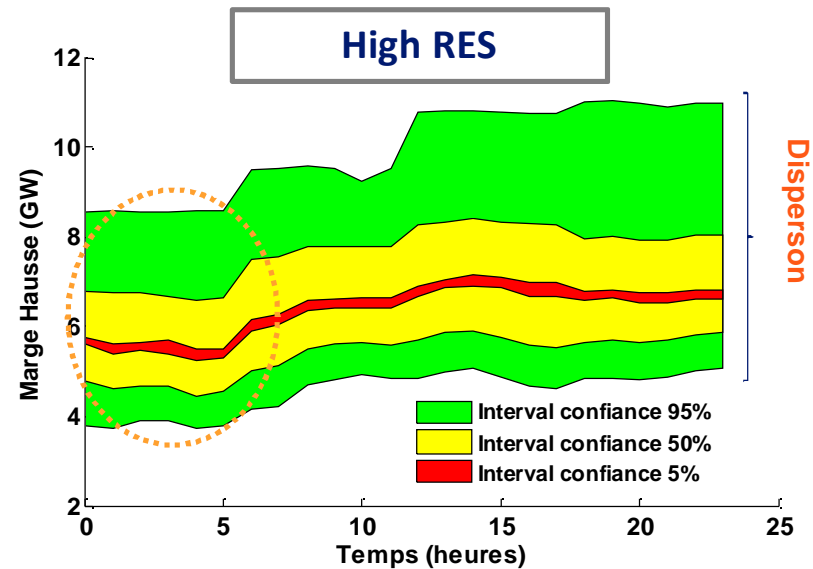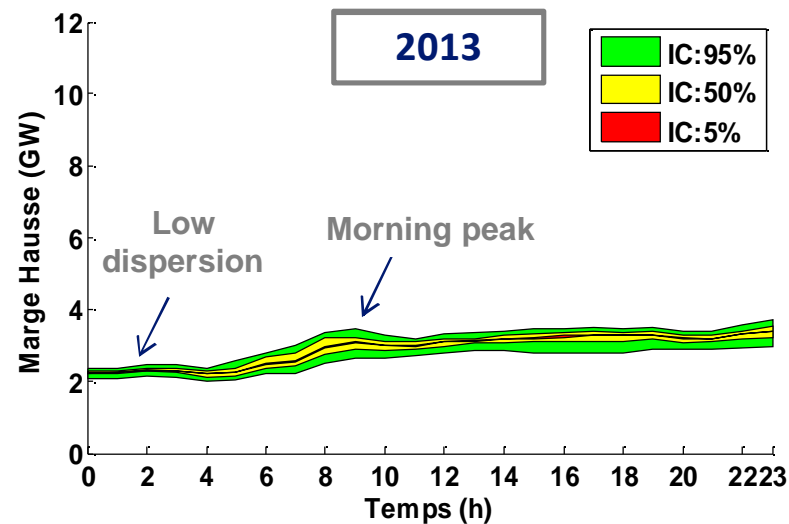
The operation margin profile changes and in the future critical periods will no longer be driven by demand => need for dynamic calculation of operation margin and reserve requirements

# Intra-day forecasts and larger balancing areas allow the reduction of operation margins within the day
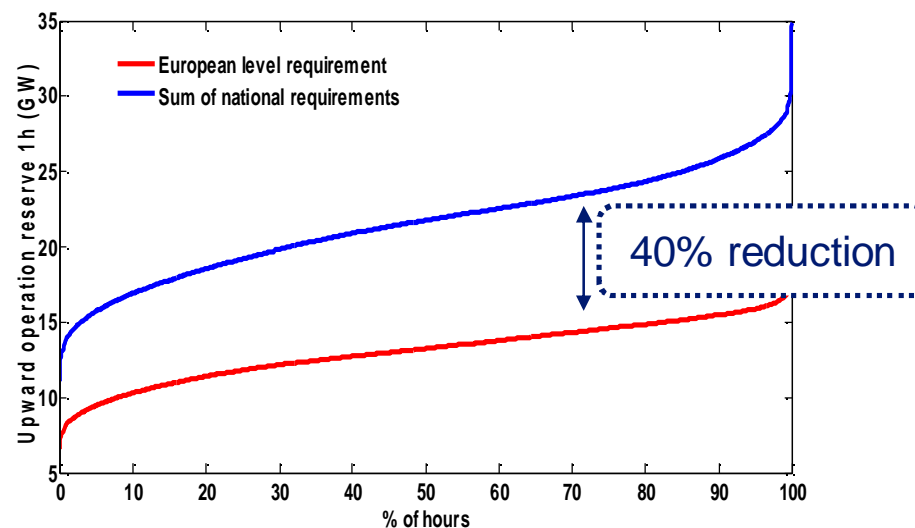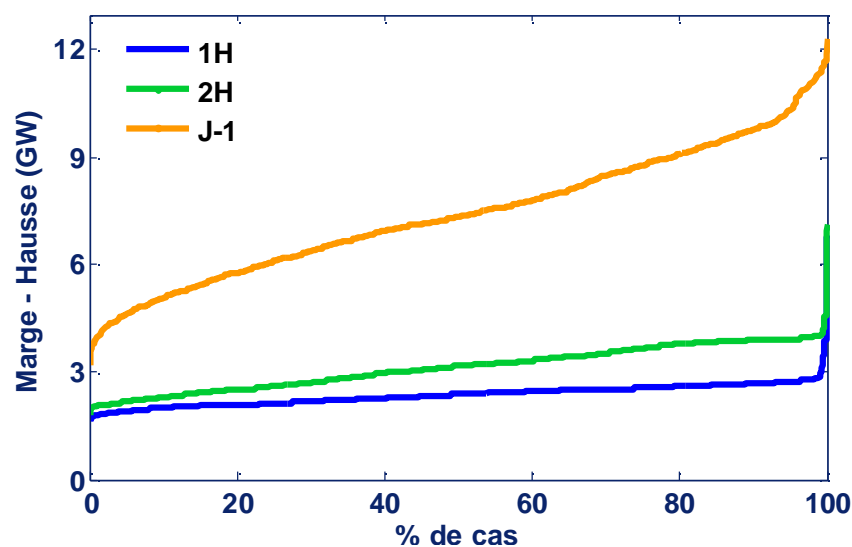
The management of uncertainty will be facilitated by an increasing near real-time dimensioning of operating reserves and by the use of larger balancing areas

The frequency dynamics of the European synchronous region is studied to study the impact of high RES

- **Development of a model od primary frequency regulation of the European synchronous continental region**

- **Calculation of the inertia of the European system, considering the characteristics of future generation units**

- **Detailed analysis of parameters influencing frequency dynamics trough sensitivity studies**

- **Evaluation of critical instantaneous RES penetrations for the European synchronous continental region**
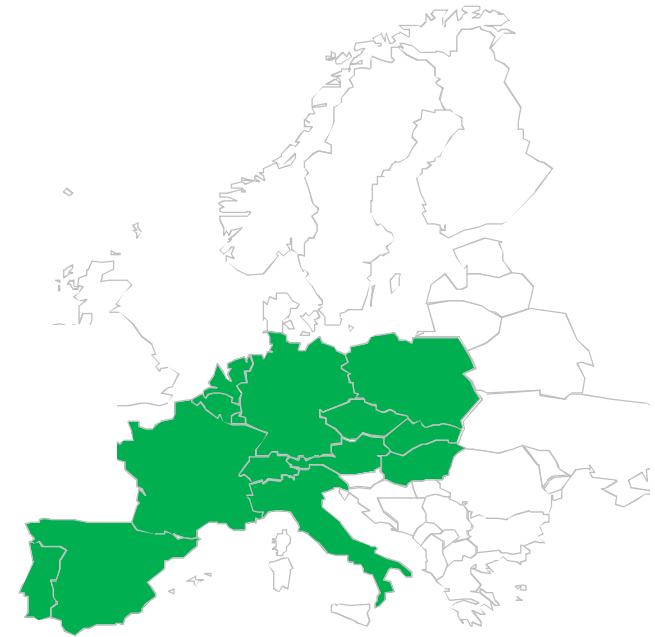
References:

Y. Wang, V. Silva, M. Lopez-Botet Zulueta, *Impact of high penetration of variable renewable generation on frequency dynamics in the continental Europe interconnected system*", **IET Renewable Power Generatio**n, Volume 10, Issue 1, January 2016, p. 10 – 16

Y. Wang, V. Silva, A. Winkels, *'Impact of high penetration of wind and PV generation on frequency dynamics in the continental Europe interconnected system'*, **13th International Workshop on Large-scale Integration of Wind Power into Power Systems** as well as on Transmission Networks for Offshore Wind Power Plants, Berlin, October 2014.

In order to maintain system security variable RES should contribute to existing and new ancillary services

The grid connection of generation units interfaced by power electronics reduces system inertia… this leads to a system less robust from a frequency stability perspective.

▶ The impact of inertia reduction is more pronounced in isolated systems such as the UK and Ireland.

▶ For very high RES penetrations protection operation become a major issue
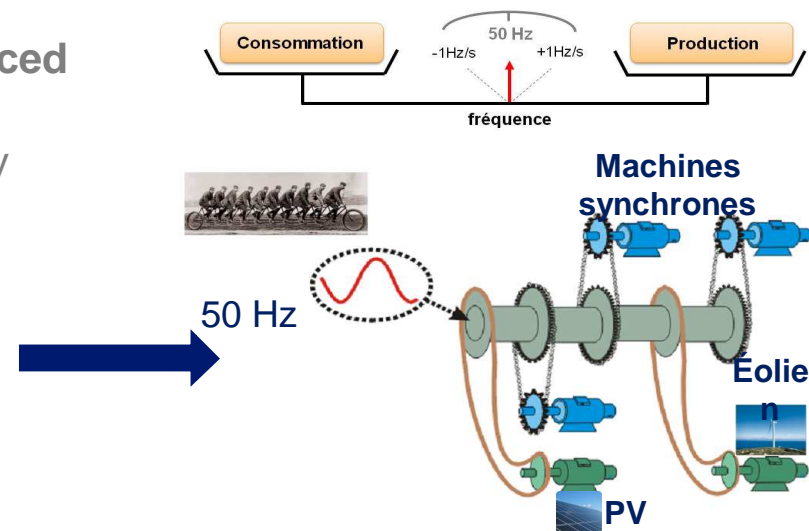
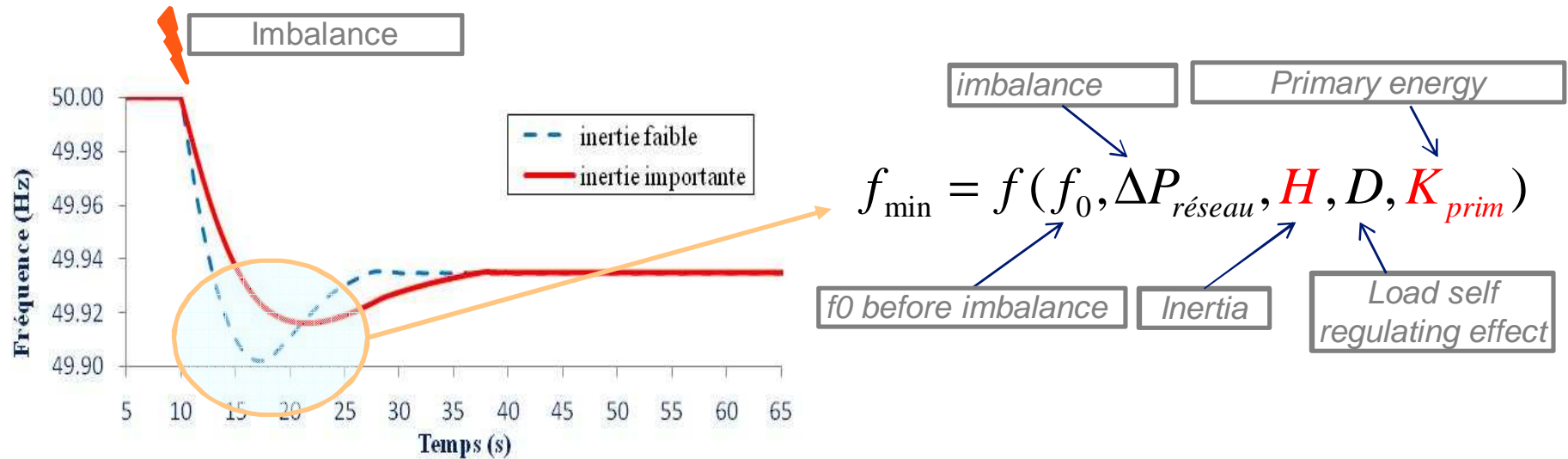**But inertia is not the only parameter that impacts system frequency stability !**

Load damping effect also contributes to frequency stabilisation!

Demand is sensitive to voltage and frequency in the sense required to stabilise the frequency

	Autoréglage *D*
Moteurs industriels	2,5 %/Hz
Charge résidentielle (lave-linge, etc.)	0,8 - 1 %/Hz
Electroniques (télévisions, lave-vaisselle, etc.) et petits transformateurs	0 %/Hz

Conso. d'un poste source suite à une perte de production
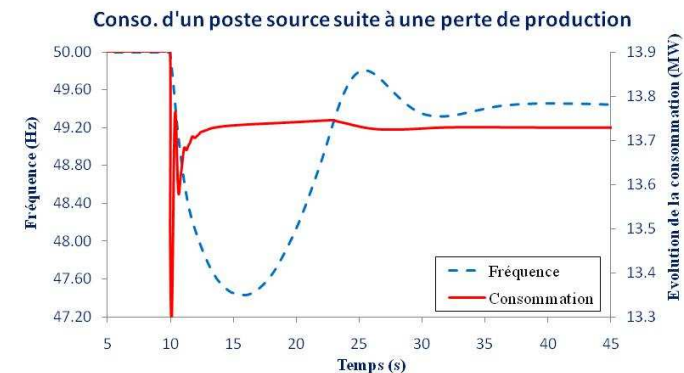
Key parameters that impact dynamic frequency stability following to a demand-generation imbalance

Imbalance

$$f_{\min} = f(f_0, \Delta P_{réseau}, H, D, K_{prim})$$

imbalance

Primary energy

f0 before imbalance

Inertia

Load self regulating effect

Assumptions used for dynamic simulation

☐ There is sufficient primary reserve and static and dynamic of deployment as today

☐ Inertia (H) and (K_{prim}) are computed for every hour using Continental model scheduling solutions
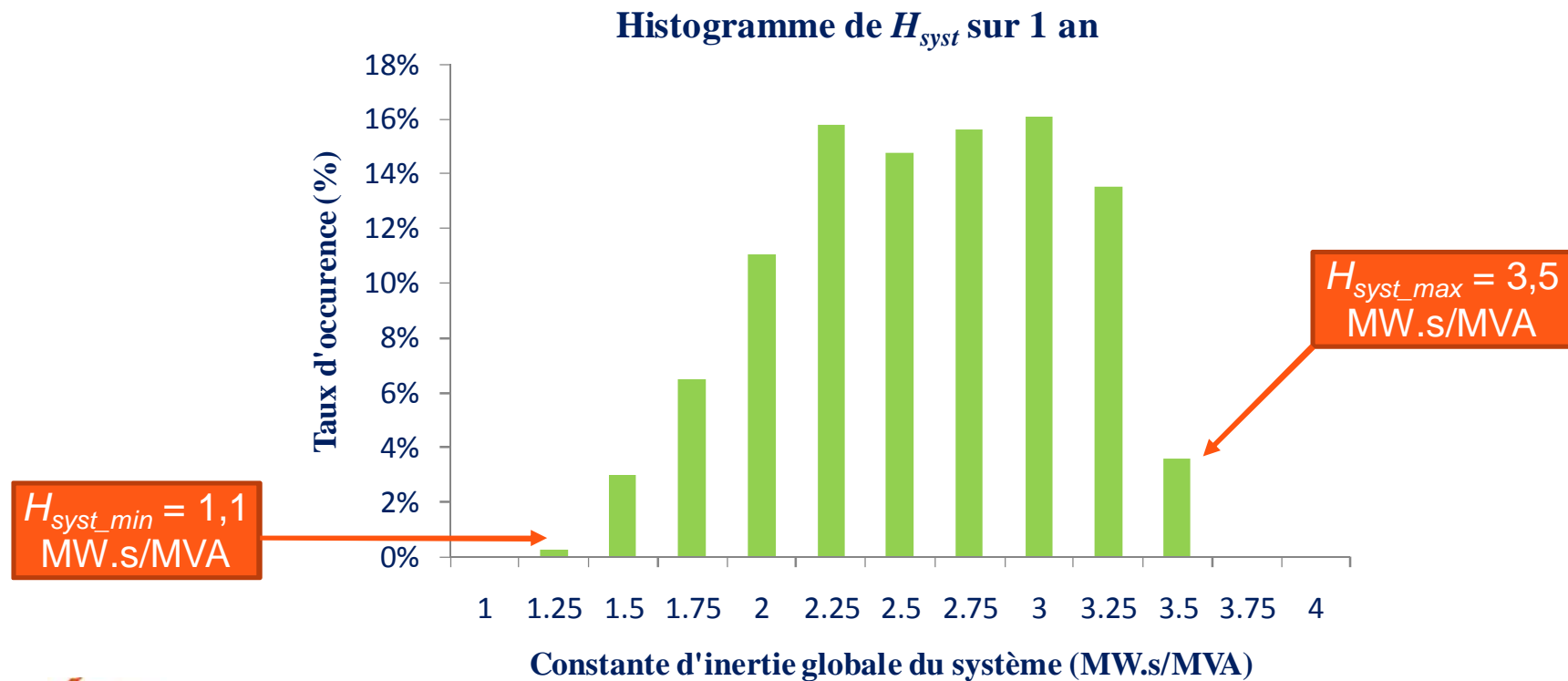
Sensitivity studies are performed to set the remaining relevant parameters

$\Delta P, f_0, D$

Objective: Identify the **critical instantaneous VG penetration** above which **dynamic frequency stability in the European continental synchronous system** could not be maintained without **load shedding actions**

Inertia in the European synchronous continental region is significantly reduced when compared to today's levels

- Today, l'ENTSO-E estimates an inertia of $H \approx 5$ MW.s/MVA for the European synchronous region

- With « 60% RES », system inertia lies in the interval [2,25 3,25] MW.s/MVA during 70% of the time and is very variable from one period to the next

Histogramme de H_{syst} sur 1 an

$H_{syst\_min} = 1,1$ MW.s/MVA

$H_{syst\_max} = 3,5$ MW.s/MVA

Taux d'occurence (%)

Constante d'inertie globale du système (MW.s/MVA)

The integration of a large share of variable generation leads to critical situations during wind nights

Analysis of the <u>European synchronous system</u> (Nordpool, UK and Ireland are not part of it) with variable RES penetration between 35 and 38% depending on the weather year

Critical periods: demand < 250 GW and instantaneous VG penetration > 25 %

During the critical periods the generation from variable RES may need to be limited to preserve system security.

Security level

Load shedding
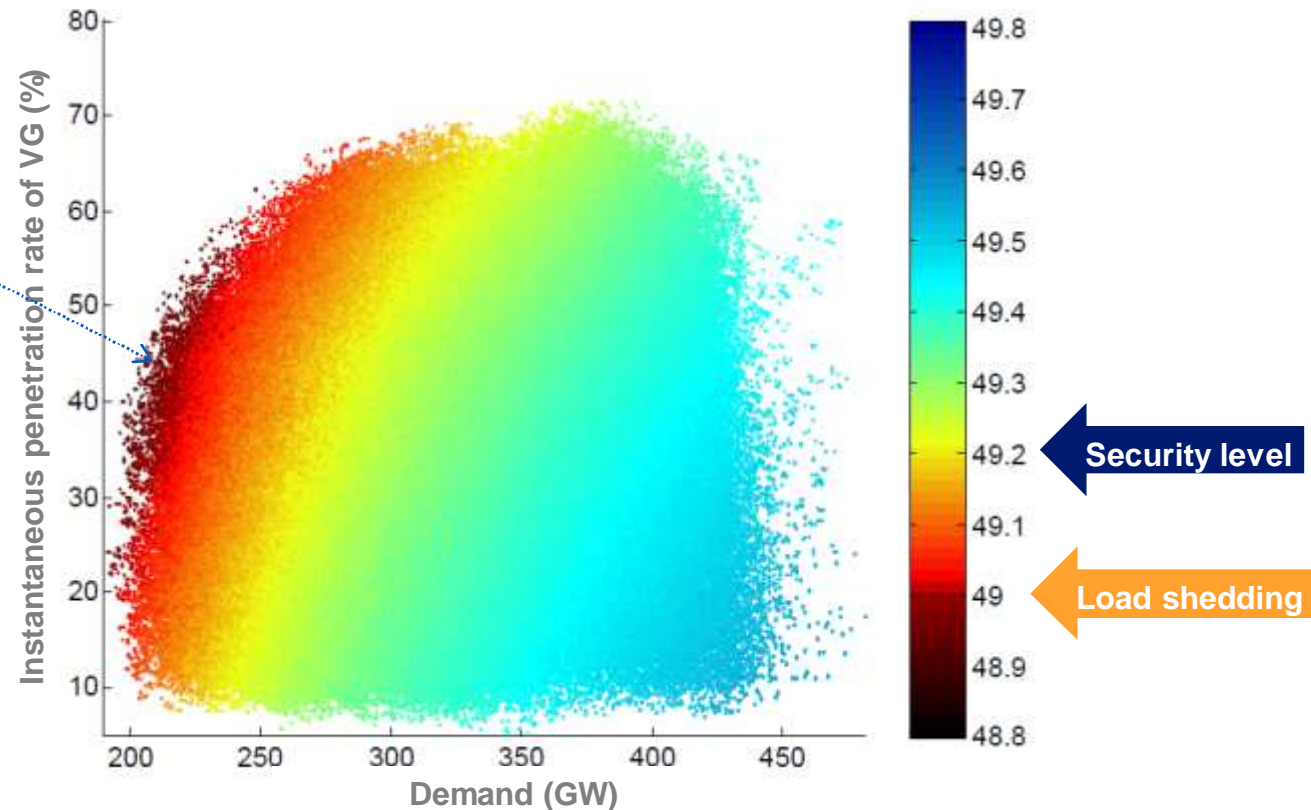
When variable RES displace a significant share of conventional plant they also need to contribute to ancillary services as well as "new services" to compensate the reduction of inertia

THANK YOU FOR YOUR ATTENTION!

Report available from :
http://chercheurs.edf.com/fichiers/fckeditor/Commun/Innovation/departements/SummarystudyRES.pdf