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

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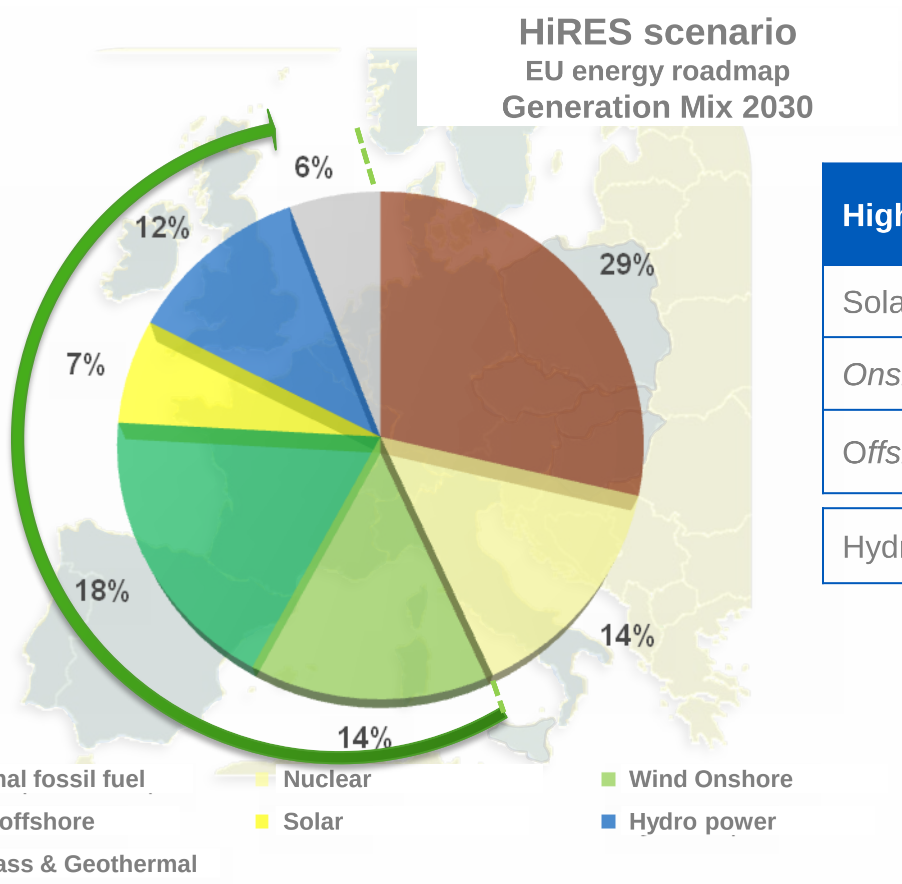
Simulation of the EU Energy Roadmap « HiRES 2030 » scenario

60 % RES
(generation)

40 % Wind & Solar

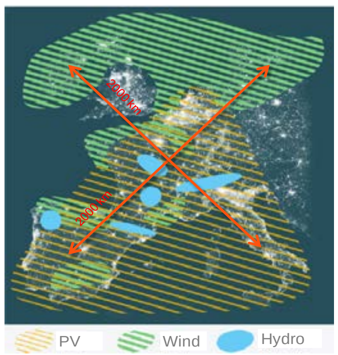


High RES 2030	GW	Load factor (h/yr)
Solar (PV)	220	1100
Onshore wind	280	1900
Offshore wind	205	3200
Hydro	120	3800

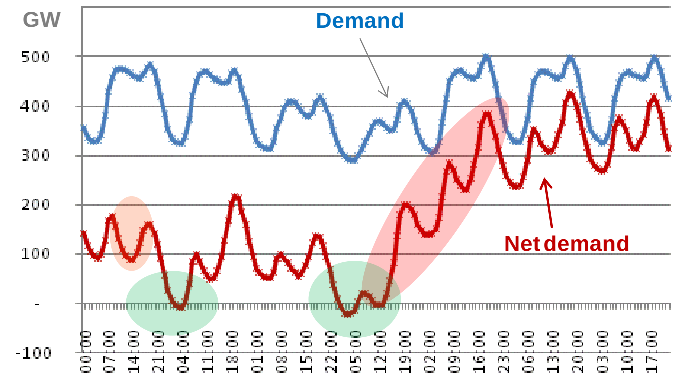
Fuel	Price
Coal	86 €/t
Gas	10 €/MMBtu
Oil	107 €/baril
CO_2	35 €/t

What is this study about?

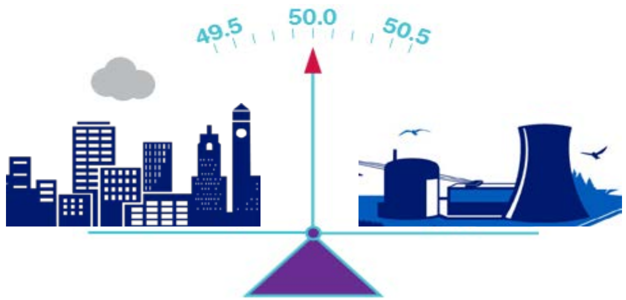
Connecting RES and load



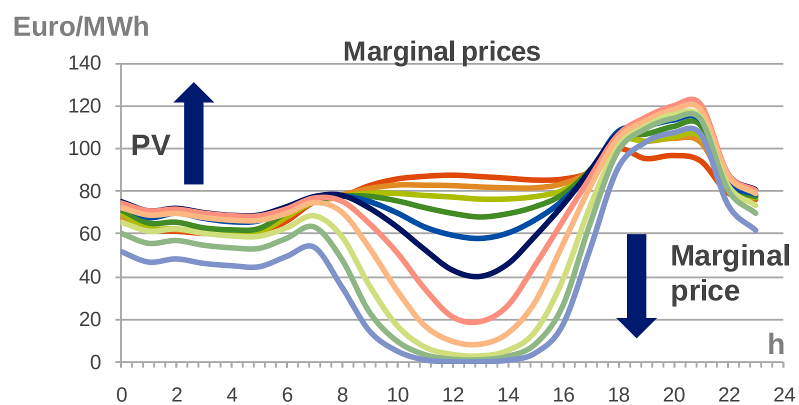
Flexibility to handle variability



Keeping the lights on



Balancing the economics



And the good news are…

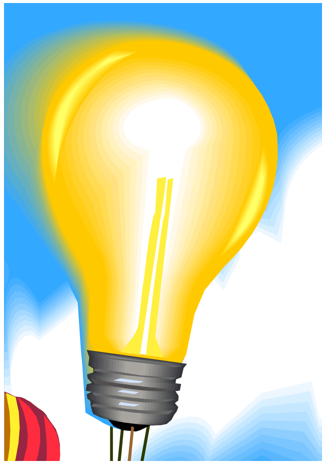
The lights will stay on so no emerging market for candles!

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

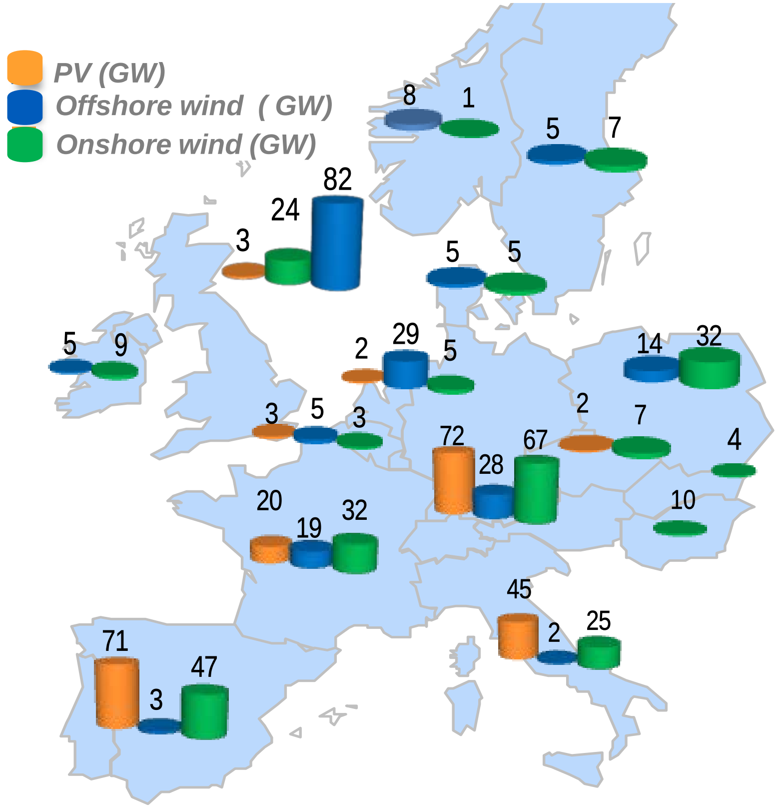
Storage and active demand may to a certain extent supplement generation to balance supply and demand

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

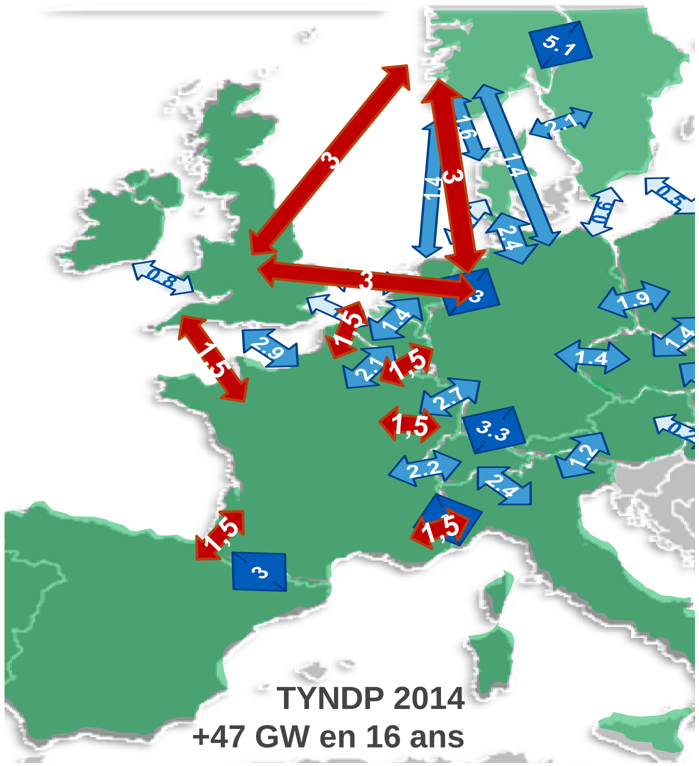
The pace of deployment of RES should be optimised in order to limit costs of storage or excessive curtailment

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

RES geographical distribution



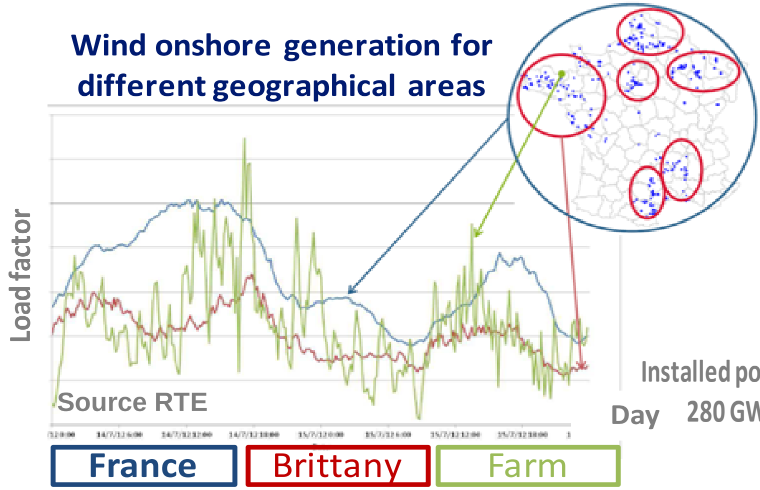
Network development scenario

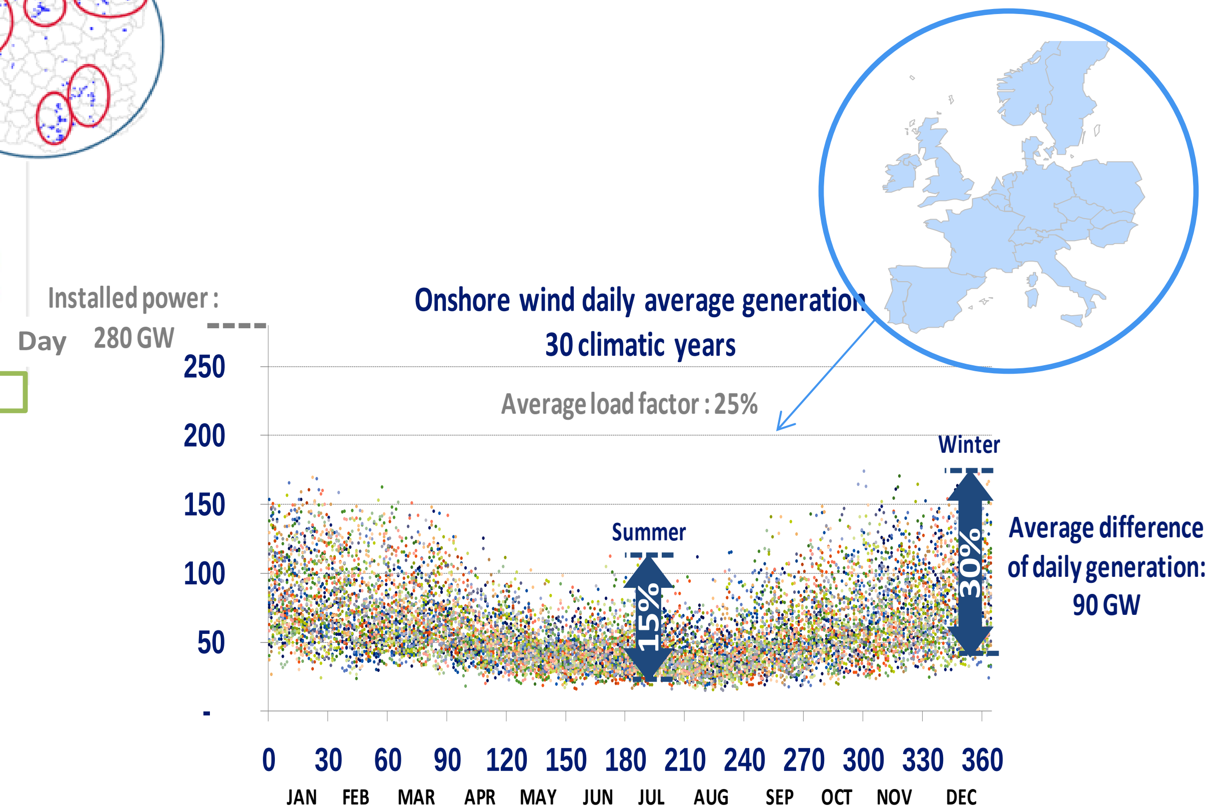


Interconnection reinforcement (GW) similar to TYNDP 2014

Interconnection reinforcement TYNDP 2010 (GW)

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

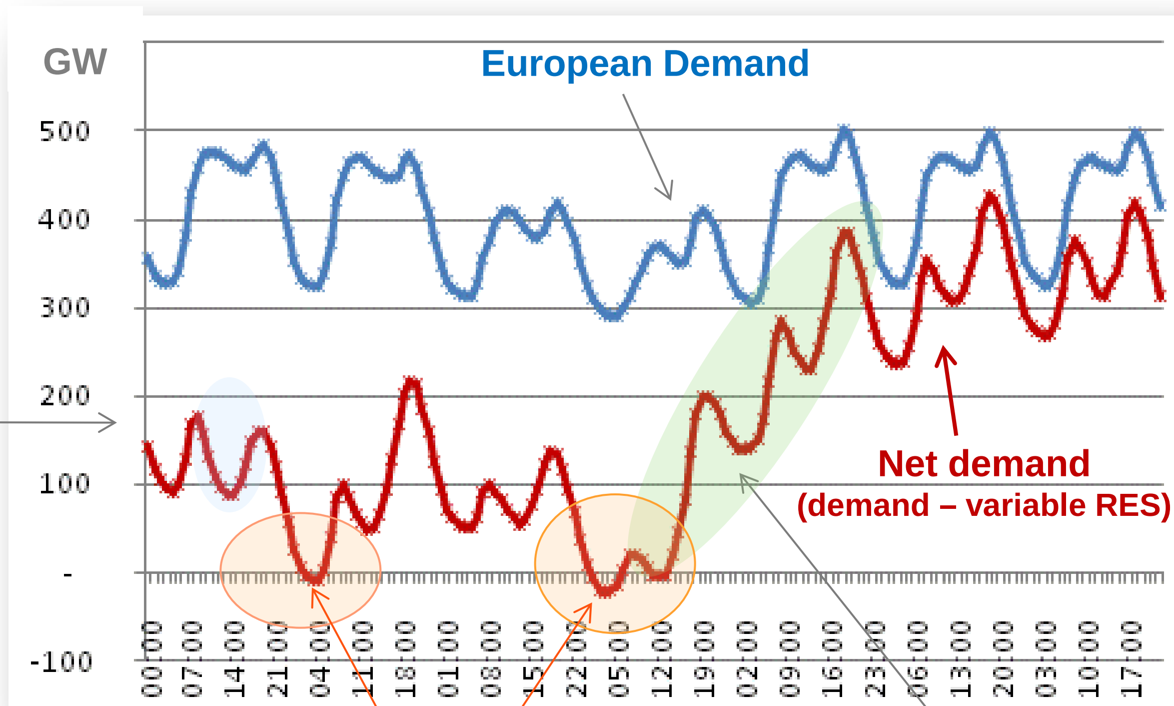




You can reduce the variability of wind and PV at local level but the correlation in wind regimes acts as a limit at continental level

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

Middle of the day valley

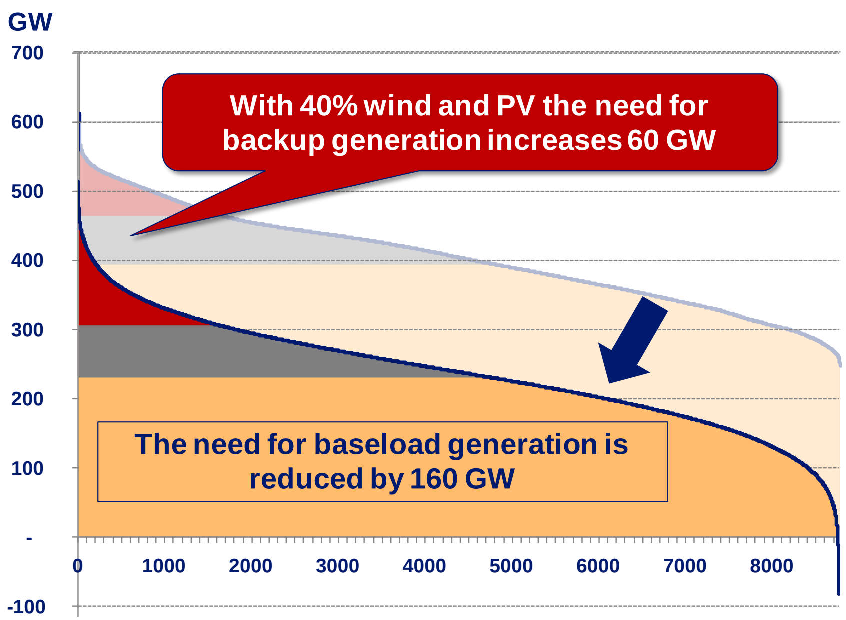


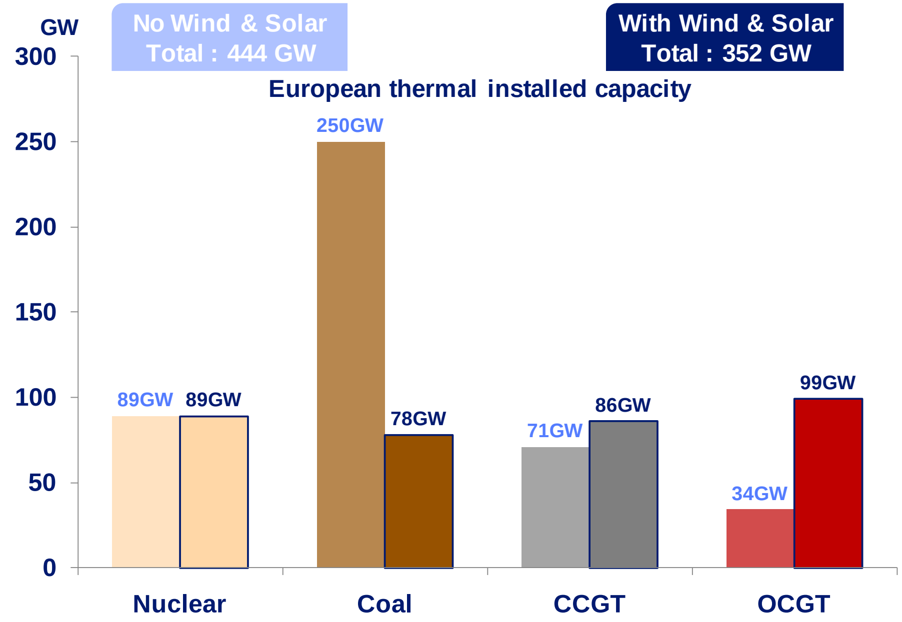
Penetration of RES > 100 %

400 GW ramp between Sunday and Monday

RES need to provide downward flexibility as well as ancillary services

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





Average CO_2 with 60% RES = 125 g CO_2 /kWh

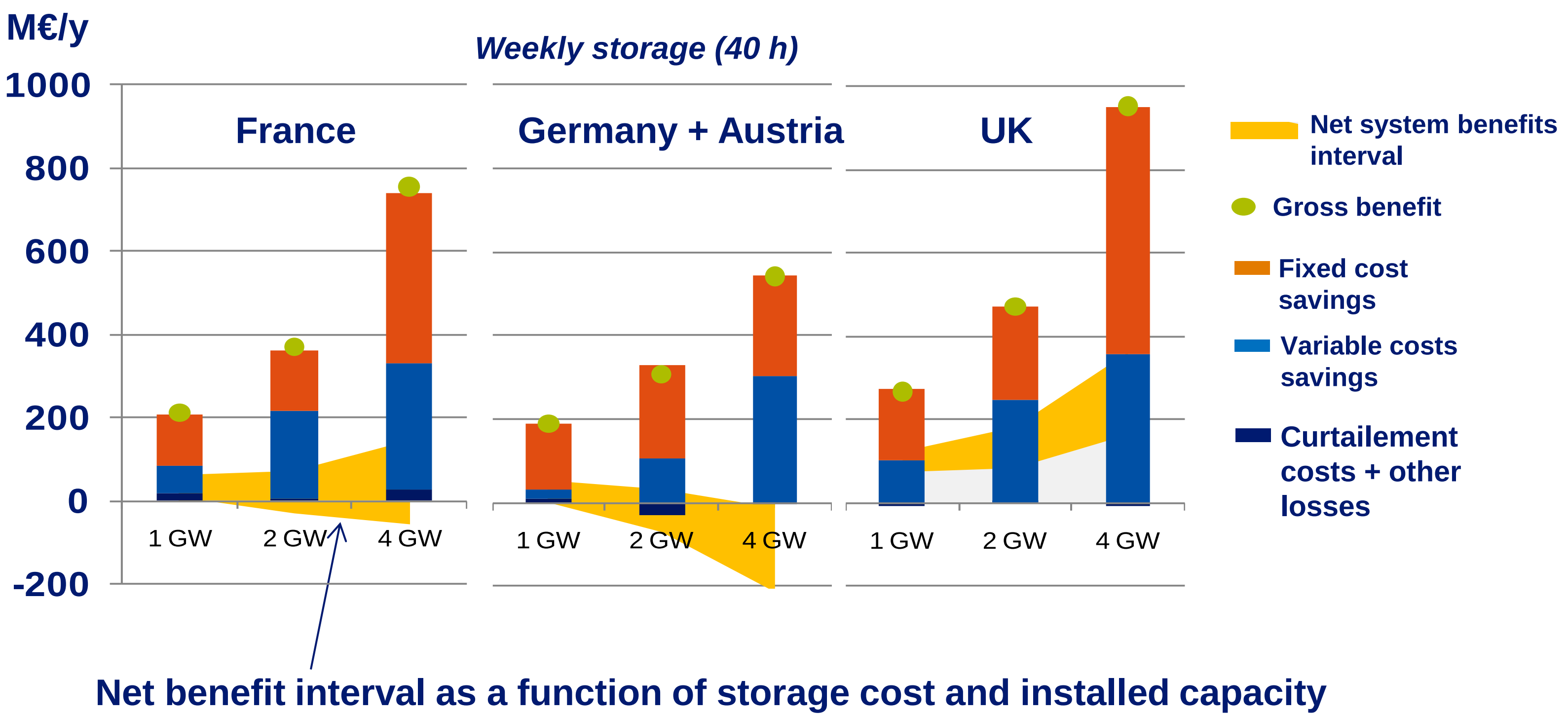
Average CO_2 with additional coal/gas replacement = 73 g CO_2 /kWh

(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

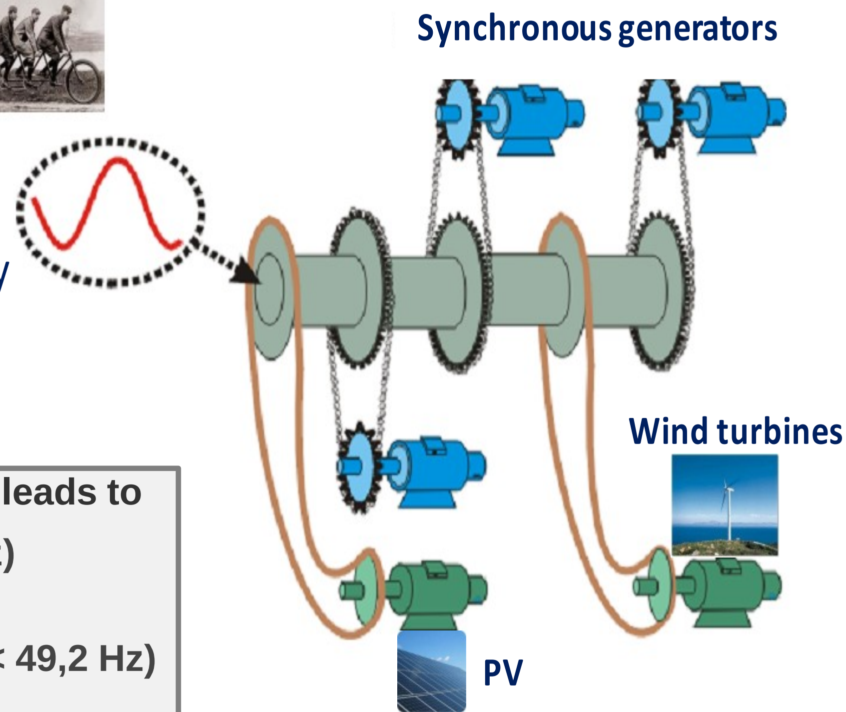
Storage and active demand may to a certain extent supplement generation to balance supply and demand

Net benefit of storage for different countries



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

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



Due to lower inertia a reference incident leads to

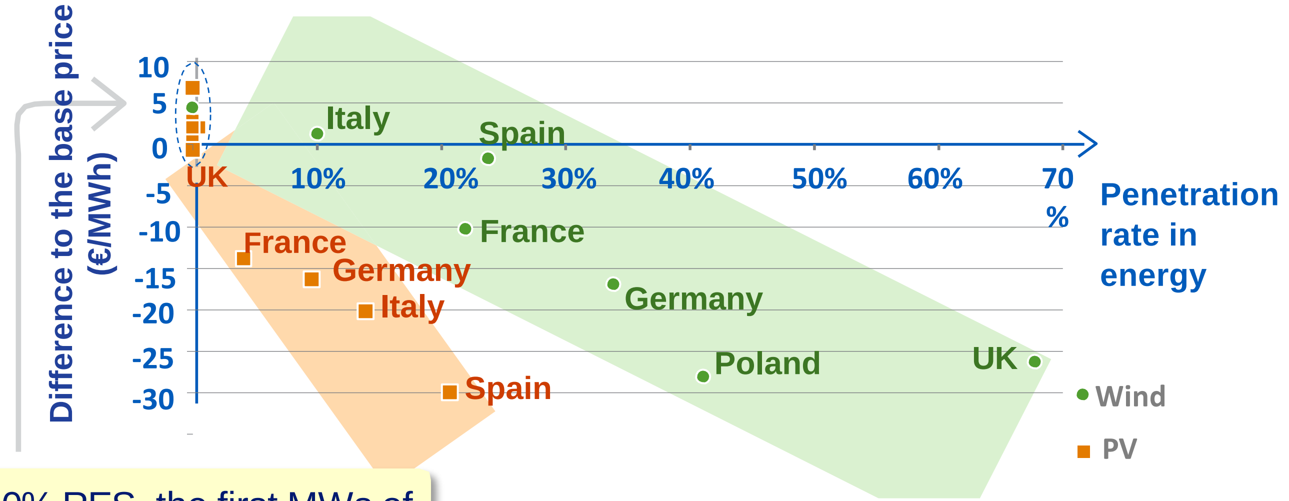
- a risk of load shedding (f< 49 Hz)
0,8 % of the time

- 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

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

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EDF R&D

Modeling the European interconnected system is a challenging task

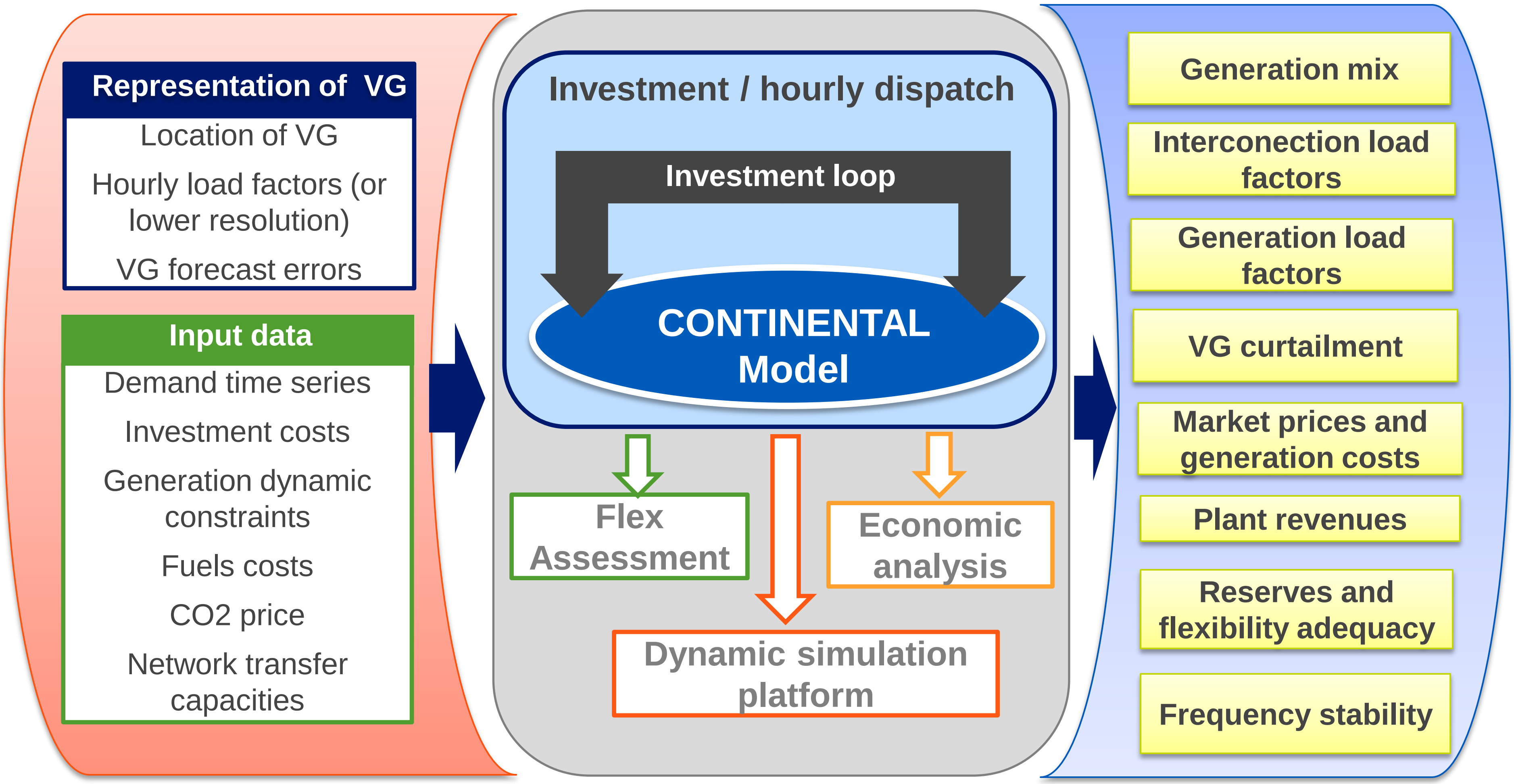
In order to represent a “realistic” European system, models should include:

- 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



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:

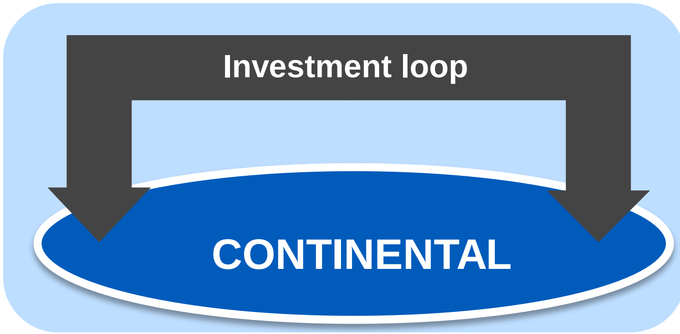
- Load duration curve based heuristic to propose a candidate solution
- Validation of the heuristic solution solving the hourly load-generation dispatch => creates an marginal cost signal that feeds the investment loop

The generation mix needs to respect an adequacy criterion

- 3h/year with marginal price = VOLL

INPUT DATA

Demand Variable generation profiles Interconnection constraints	Storage Investment costs Commodity prices CO2 price



OUTPUT

Optimal thermal generation mix Production dispatch Production costs	Market clearing prices CO2 emissions Hydro stock level paths 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

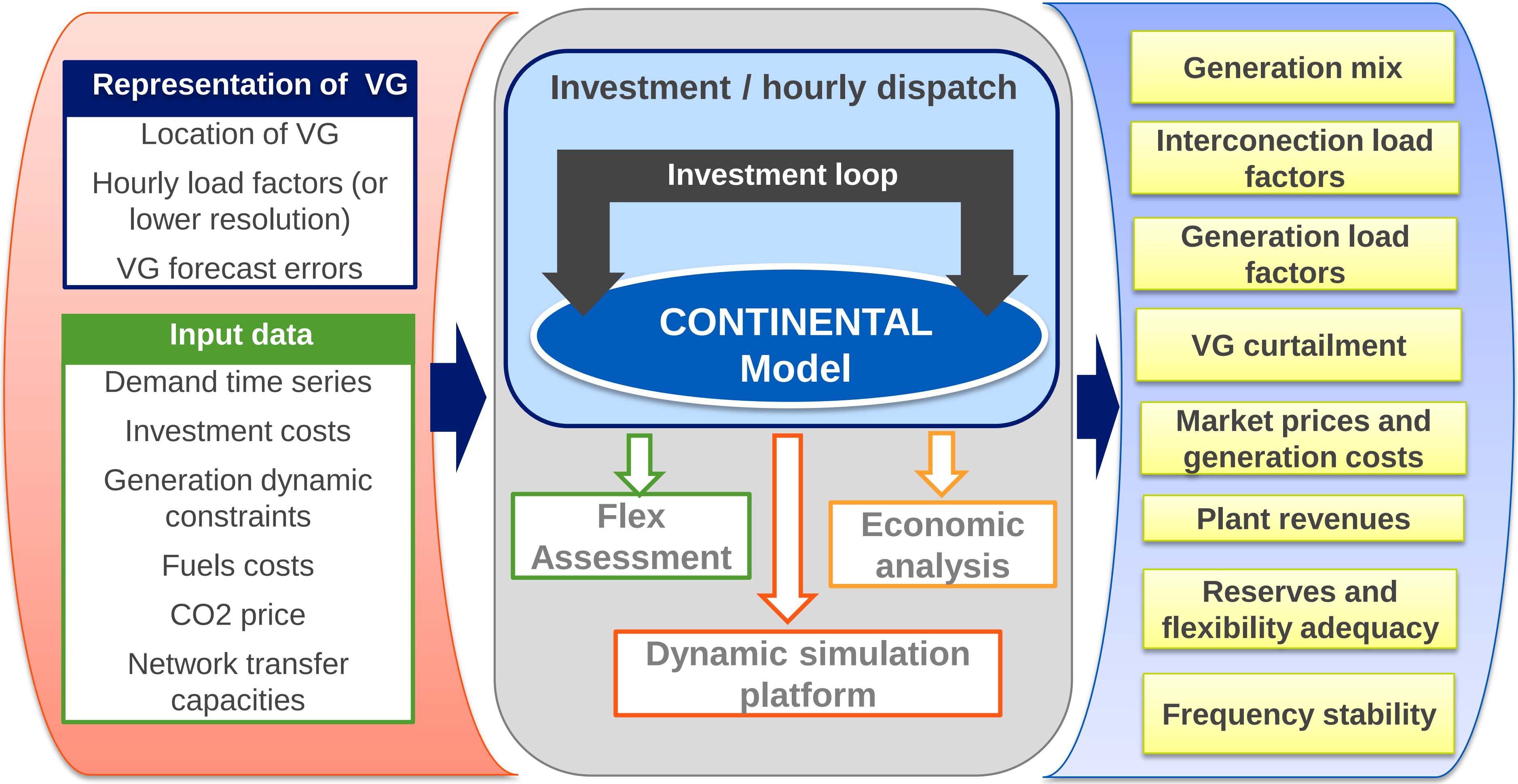
Constraints include primary, secondary and tertiary reserve and generation dynamic ratings

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

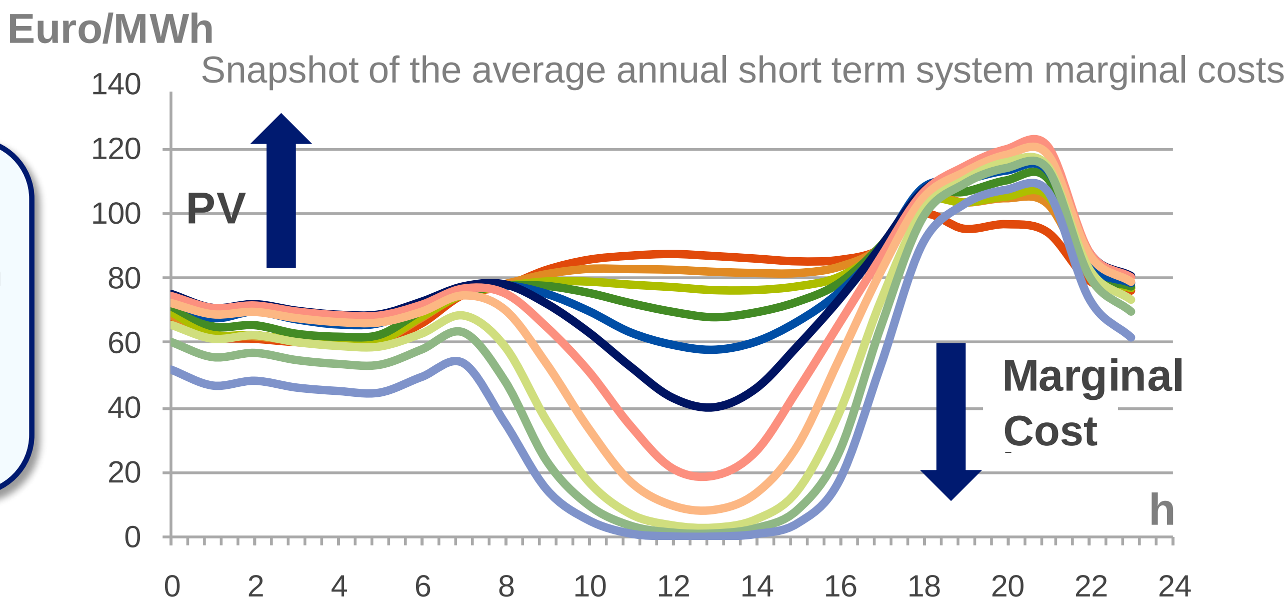
Reference: Langrene, N., van Ackooij, W., Breant, F., "*Dynamic Constraints for Aggregated Units: Formulation and Application* », **Power Systems, IEEE Transactions on** , vol.26, no.3, Aug. 2011

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



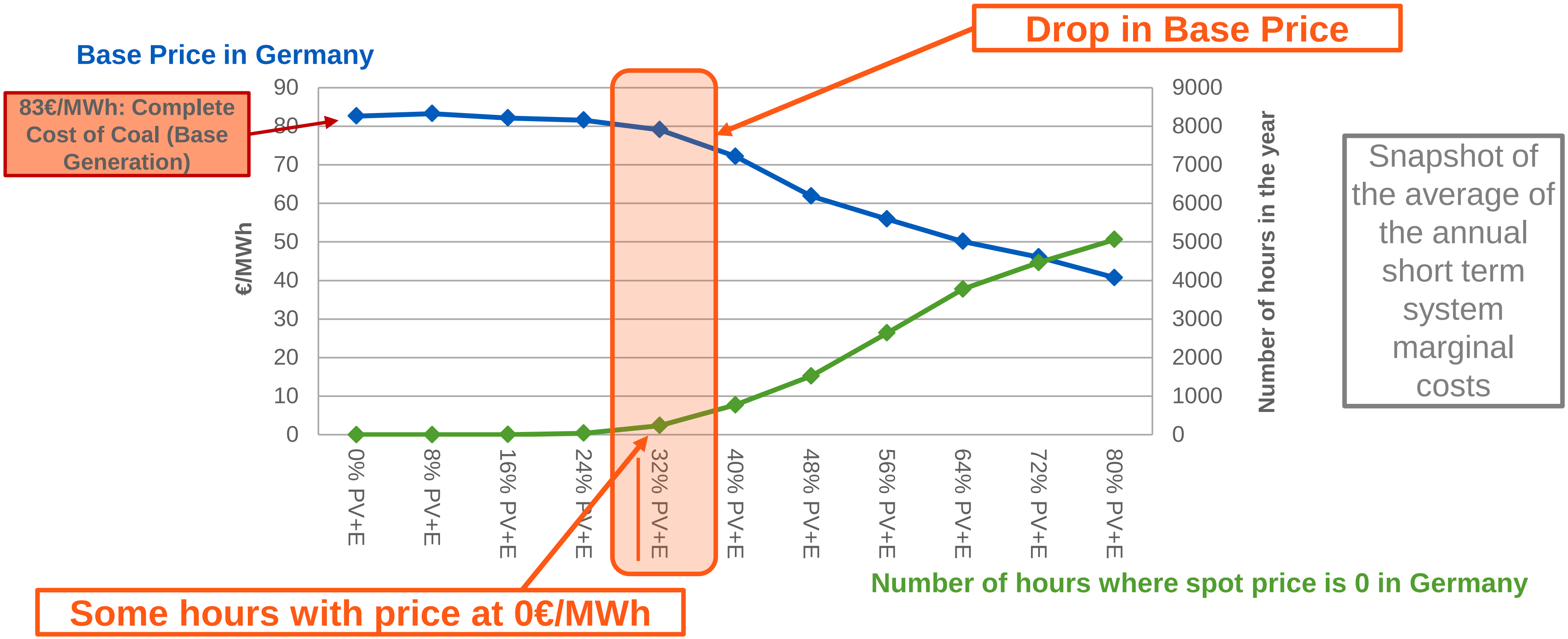
Balancing the economics

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



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

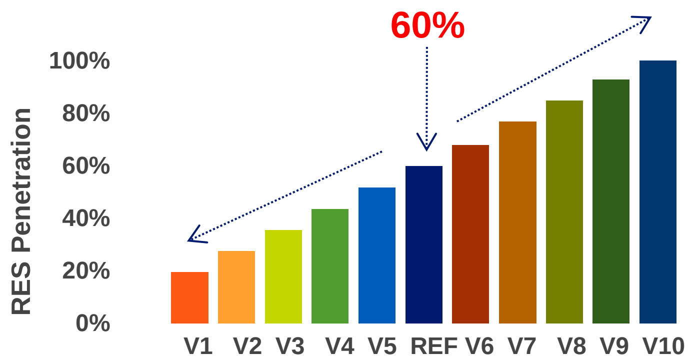


For a high penetration of RES, the notion of "base generation" disappears.

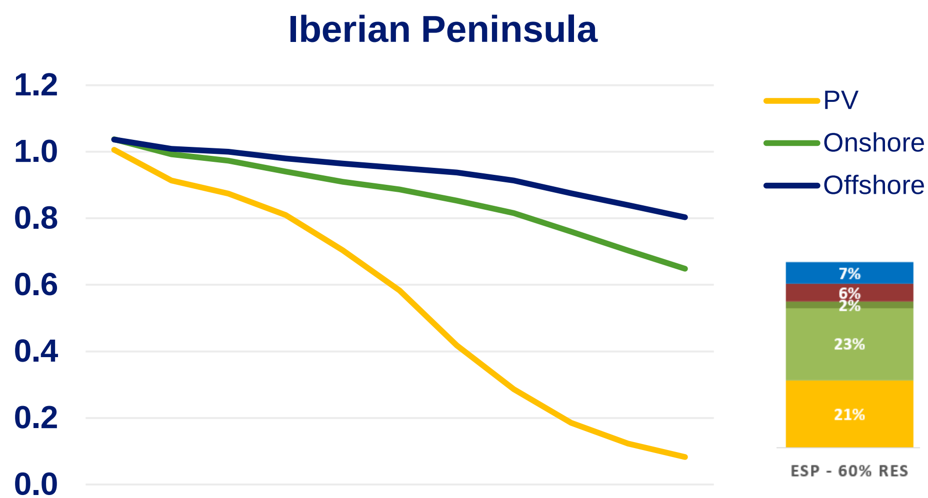
Plants need to recover their costs on fewer hours but remain profitable as long as the marginal price when operating is high enough.

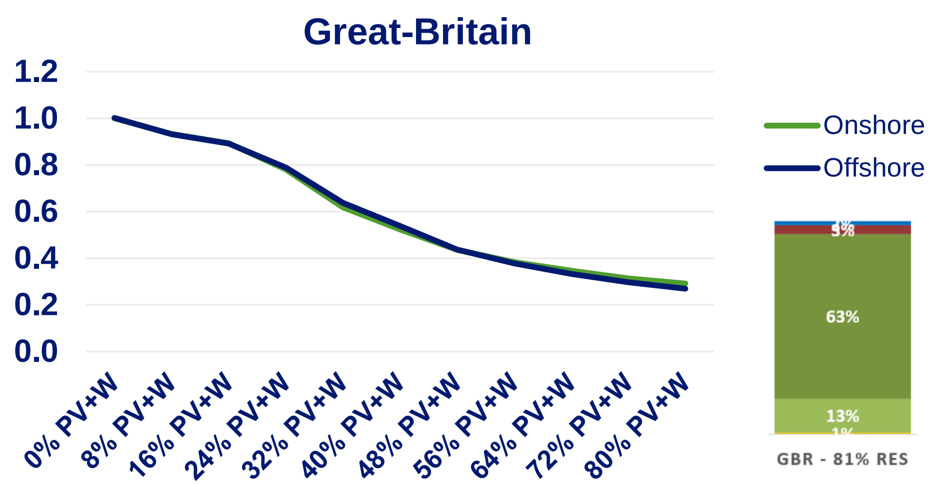
The higher the penetration of RES the lower their value factor. This effect is more pronounced for PV

Sensitivity to variable RES penetration *



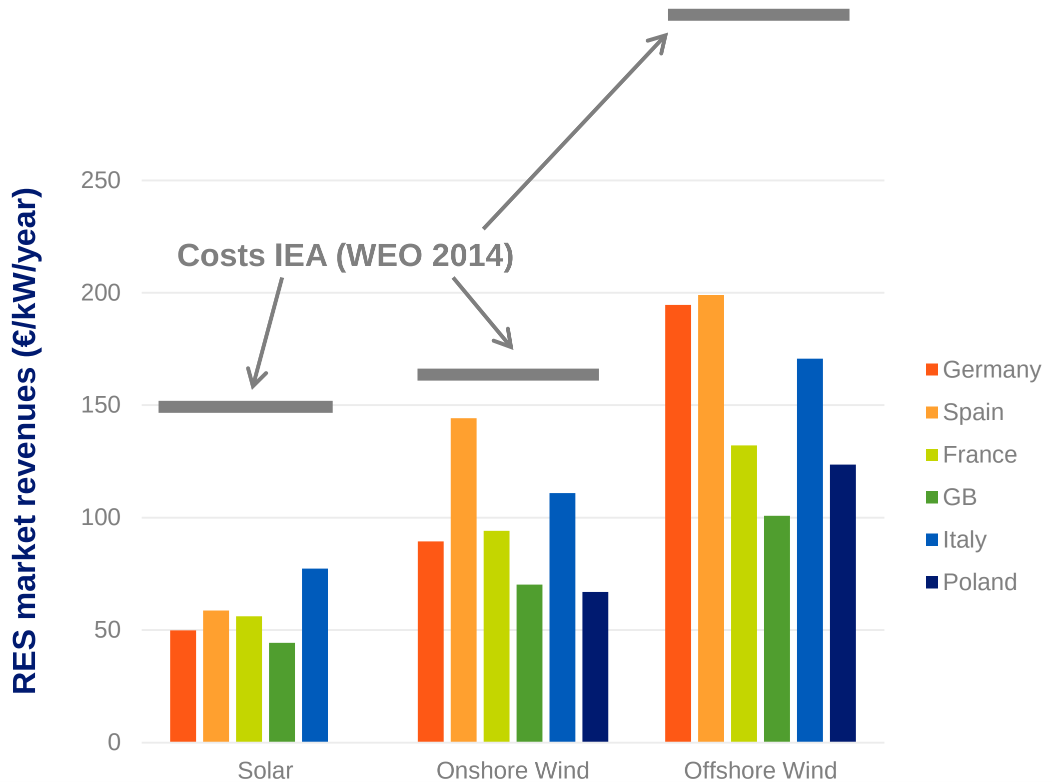
$$\text{Value Factor} = \frac{\text{RES revenue (€/MWh)}}{\text{Base Price(€/MWh)}}$$





* None of the other parameters, such as the level of interconnection, were modified.

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



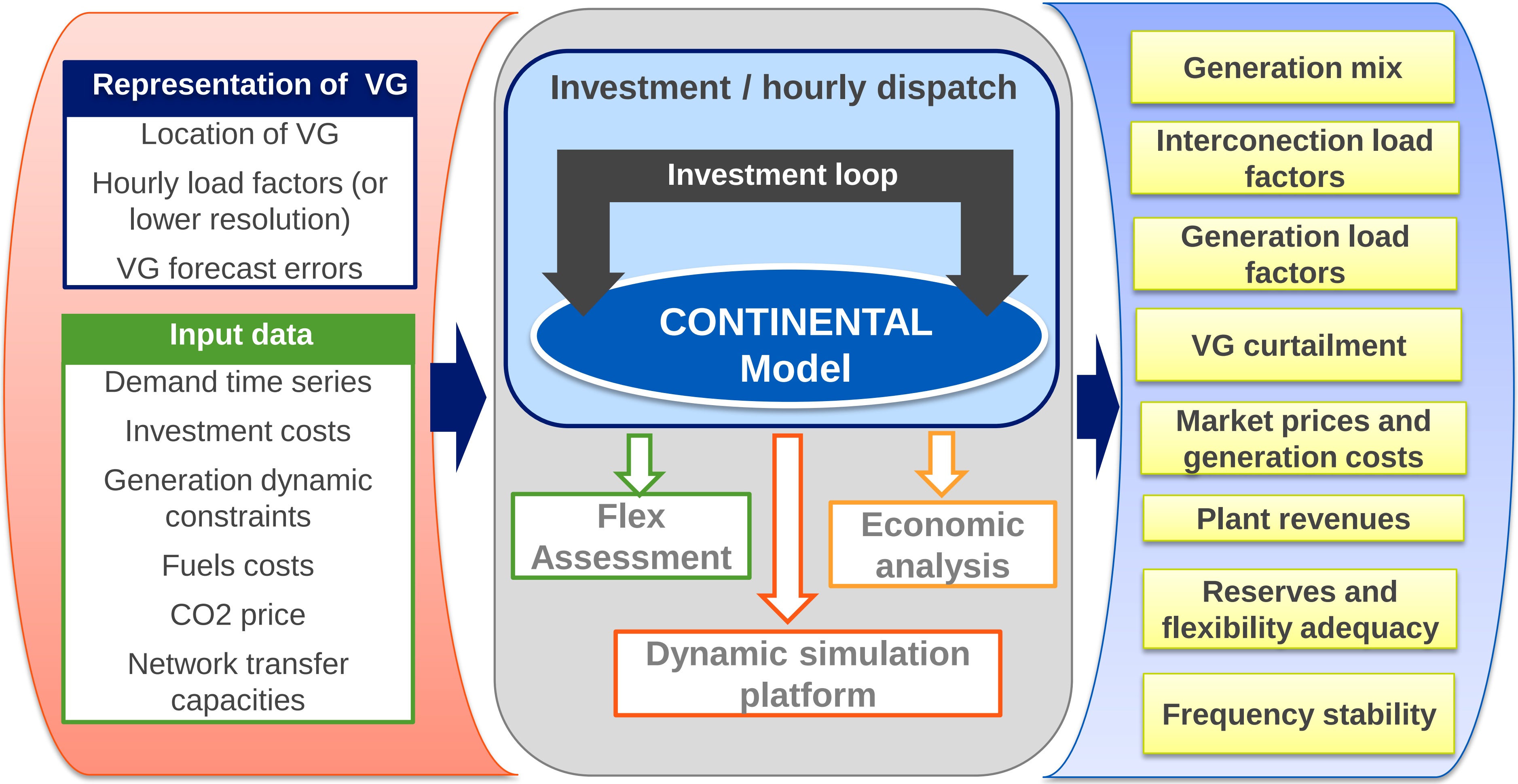
Onshore wind => economic value close to its costs.

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

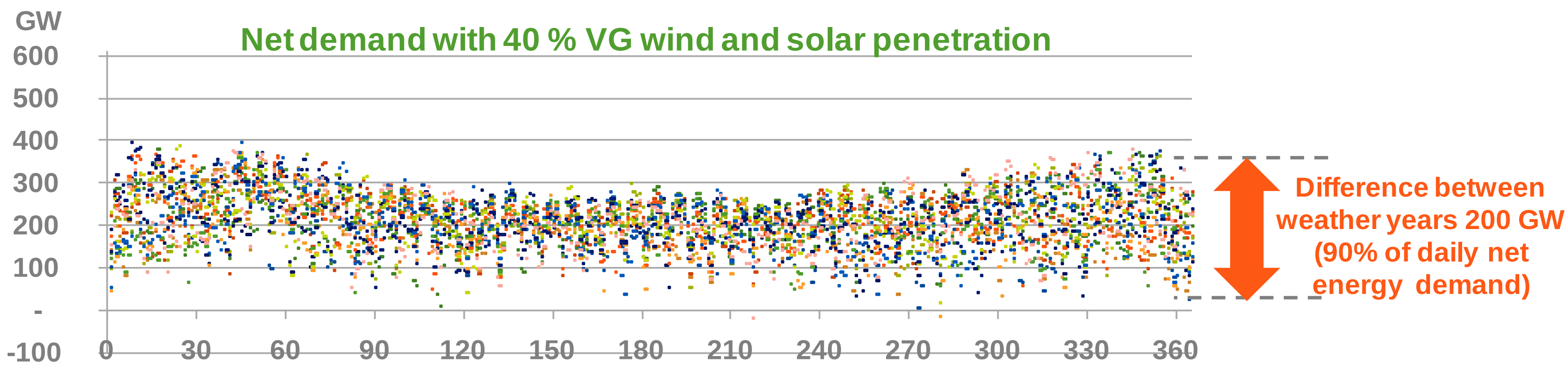
PV => low revenues of PV due to a pronounced “cannibalisation” effect

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

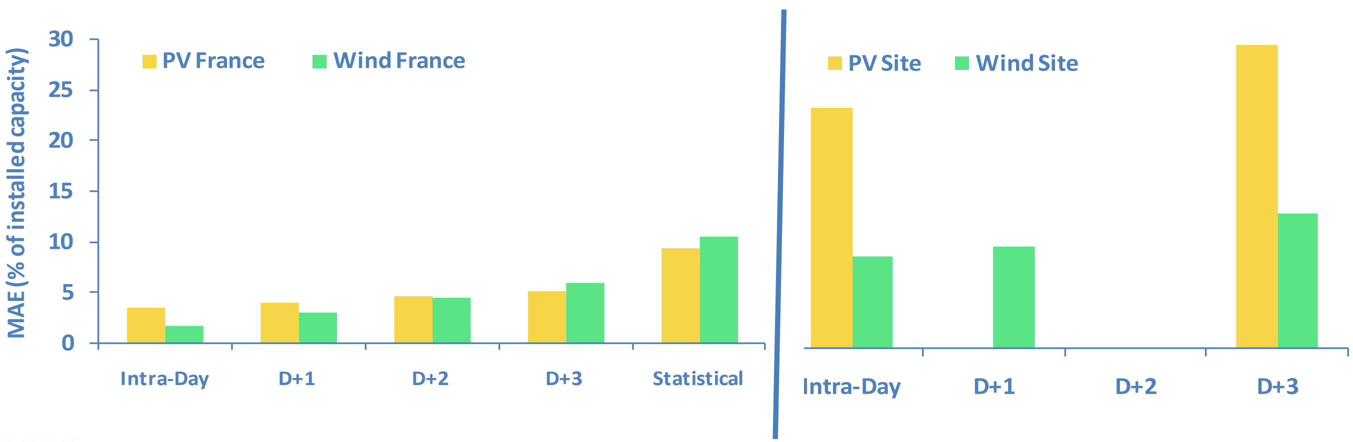
Dedicated tools are used to access the impact of short term uncertainty impact on flexibility and dynamic stability



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



Observability and forecasting are essential to reduce the operation margins required to handle load-generation balancing

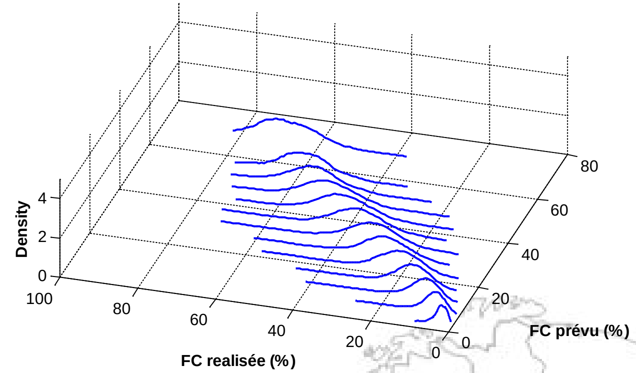


The average mean forecast error at farm level is 2 to 3 times higher than at a country level

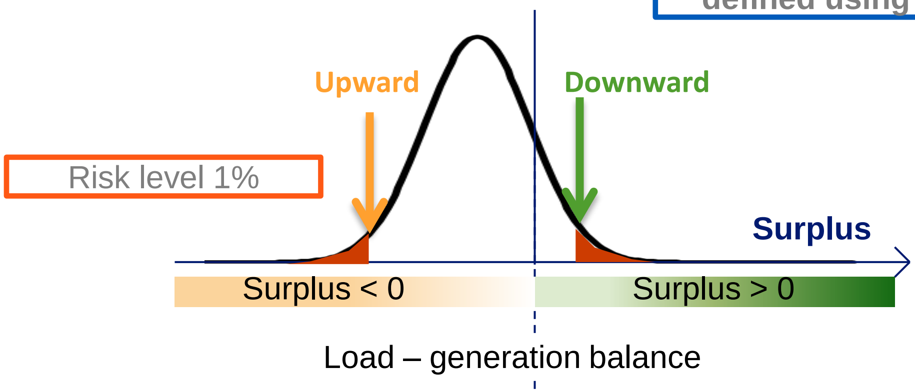
We performed a detailed analysis of operation margins and reserves for different countries for the 60% RES scenario

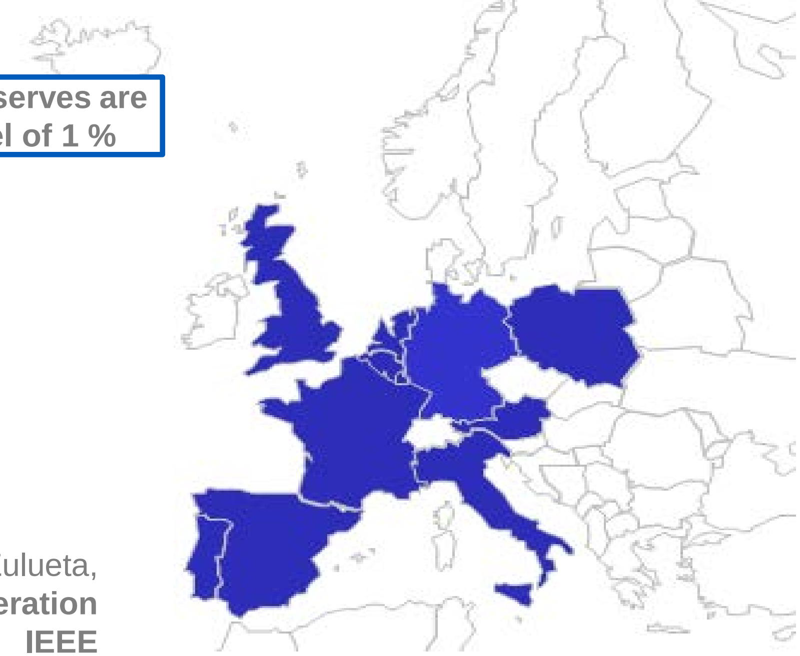
- **An innovative probabilistic approach** was **developed to compute operation margins and reserve requirements :**
  - Probabilistic models of forecast errors (wind, PV and demand) for each hour and different lead times
  - Probabilistic models of generation availability (considering outages and failure to synchronize)
  - Use of numerical convolution to characterize load-generation balancing distribution

Example of distribution of wind forecast errors



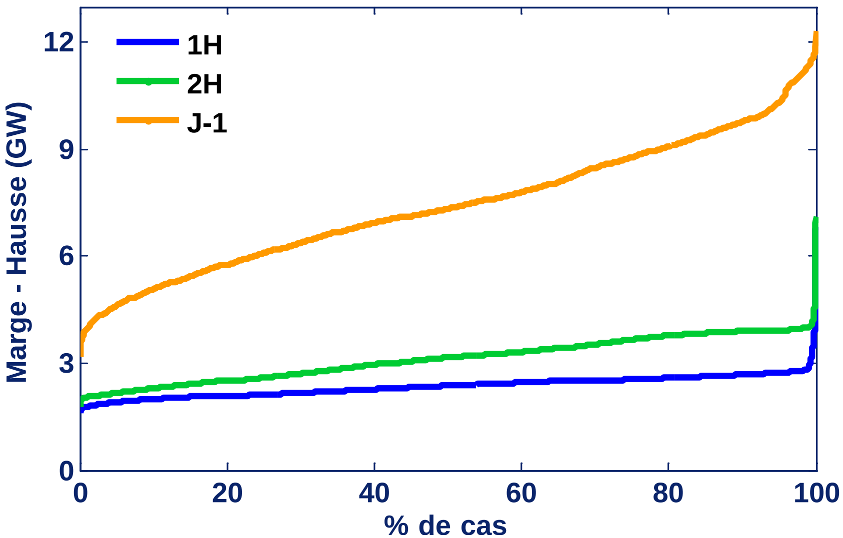
Operation margins and reserves are defined using a risk level of 1 %

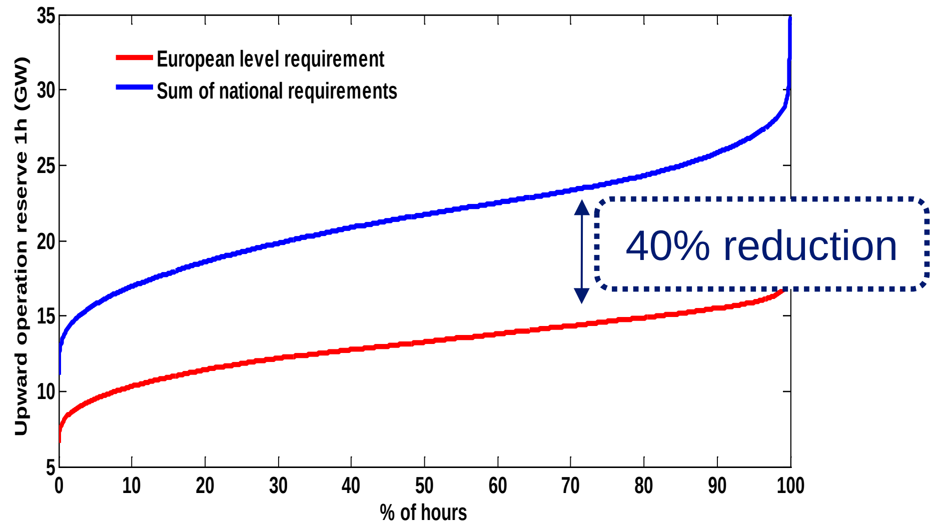




Reference: G. Prime, V. Silva, M. Lopez-Botet Zulueta, **Integration of flexibility assessment to generation planning of large interconnected systems, IEEE Transactions on Power Systems** (submitted)

Intra-day forecasts and larger balancing areas allow the reduction of operation margins within the day

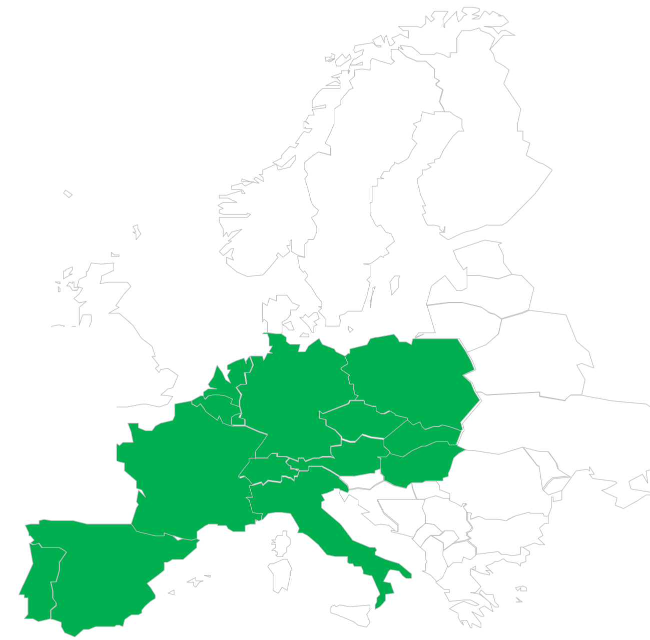




The management of uncertainty will be facilitated by an increasing near real-time dimensioning of operating reserves and by the use of larger balancing areas

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

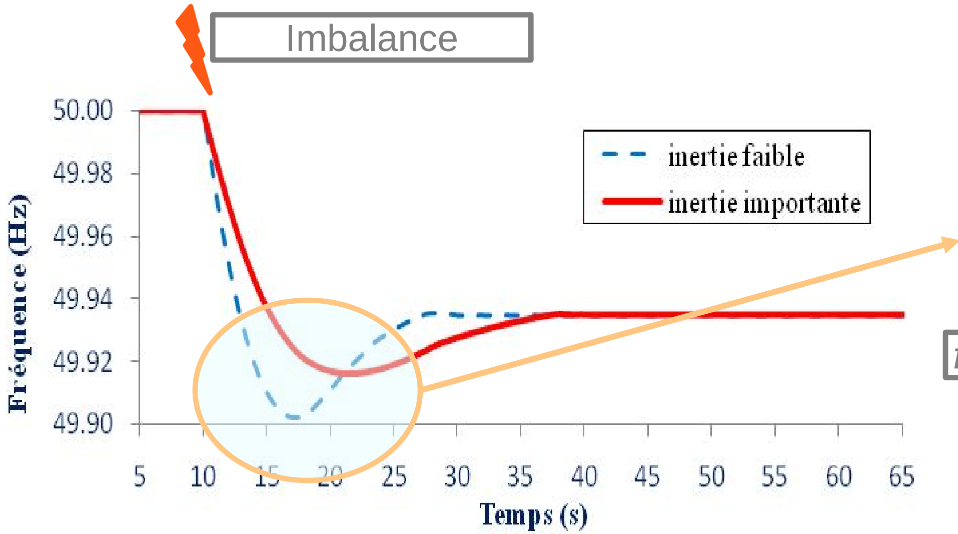


References:

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.

Key parameters that impact dynamic frequency stability following to a demand-generation imbalance



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

imbalance → $\Delta P_{réseau}$

Primary energy → K_{prim}

f0 before imbalance → f_0

Inertia → H

Load self regulating effect → D

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

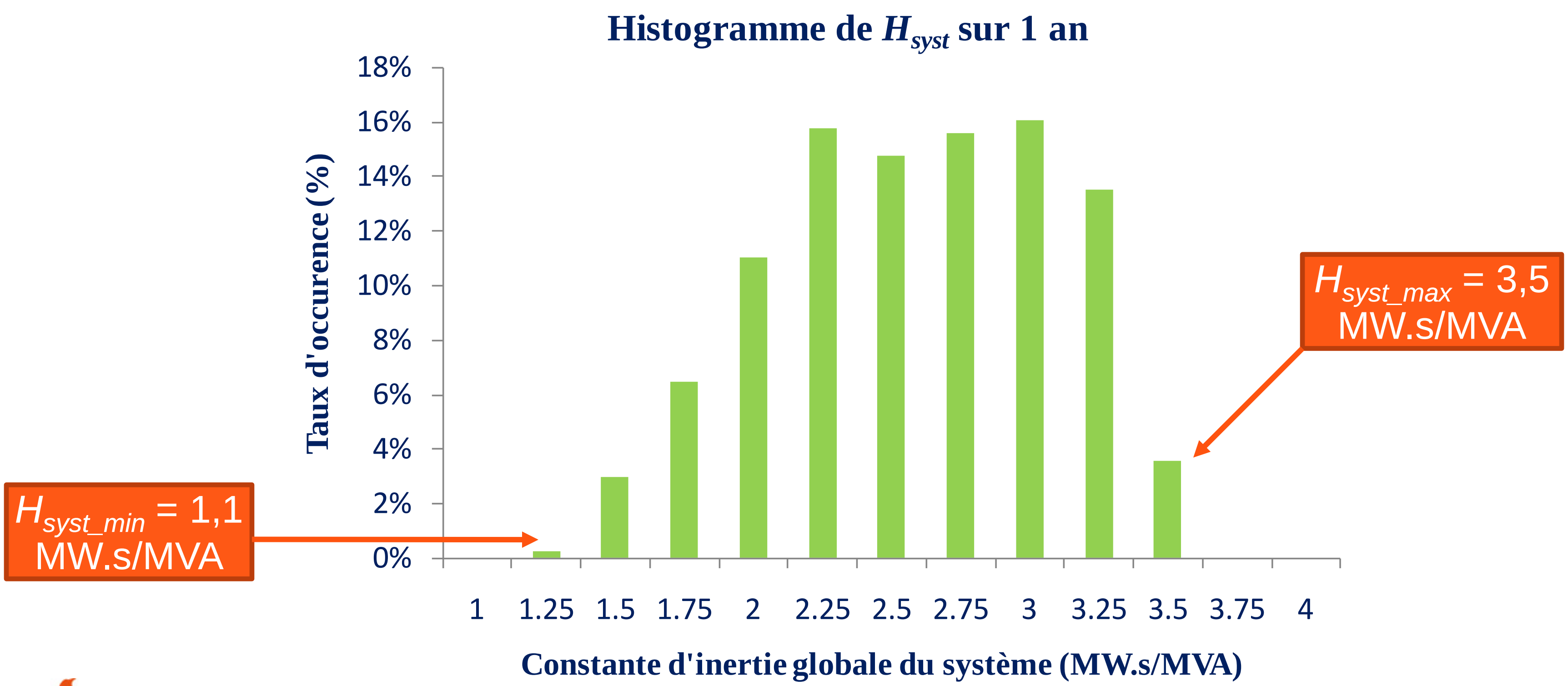
Sensitivity studies are performed to set the remaining relevant parameters

ΔP, 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

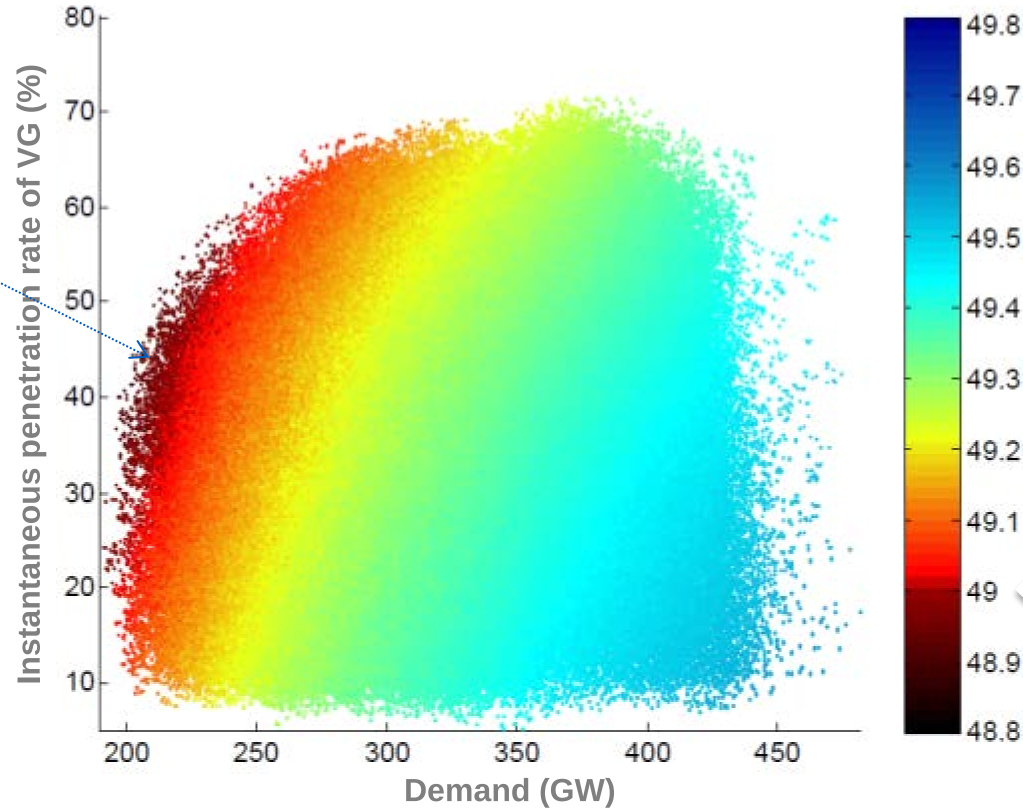


The integration of a large share of variable generation leads to critical situations during wind nights

Analysis of the European synchronous system (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