ENERGY SYSTEMS PLANNING AND THE INTERACTIONS WITH THE ELECTRICITY SYSTEM PLANNING
- AN EUROPEAN MODEL –

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EDF R&D

2015

EDF AT A GLANCE

37.9 million
customers worldwide

169,139
employees worldwide

€66.3 billion
in sales, of which
49% outside France

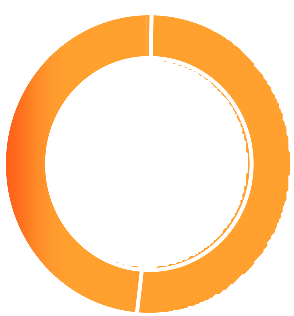
618.5 TWh
of energy generated worldwide

117.1 g
of CO_2 per kWh generated

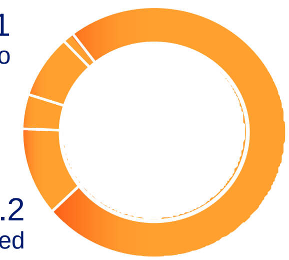
Key figures

- Electricity: covering the entire chain, from generation to transmission, distribution and supply.
- Solidly anchored in Europe: France, the UK, Poland, Italy, etc.
- Industrial operations in Asia and United States
- Natural gas: a major player

2009 sales %



2009 Group generation mix %



Total: 618.5 TWh

EDF R&D – AREAS OF ACTIVITY AND KEY FIGURES

€523 million

2012 Budget

of which 25% for environmental projects

Areas of activity

2 110 PERSONS

including

370 PhDs

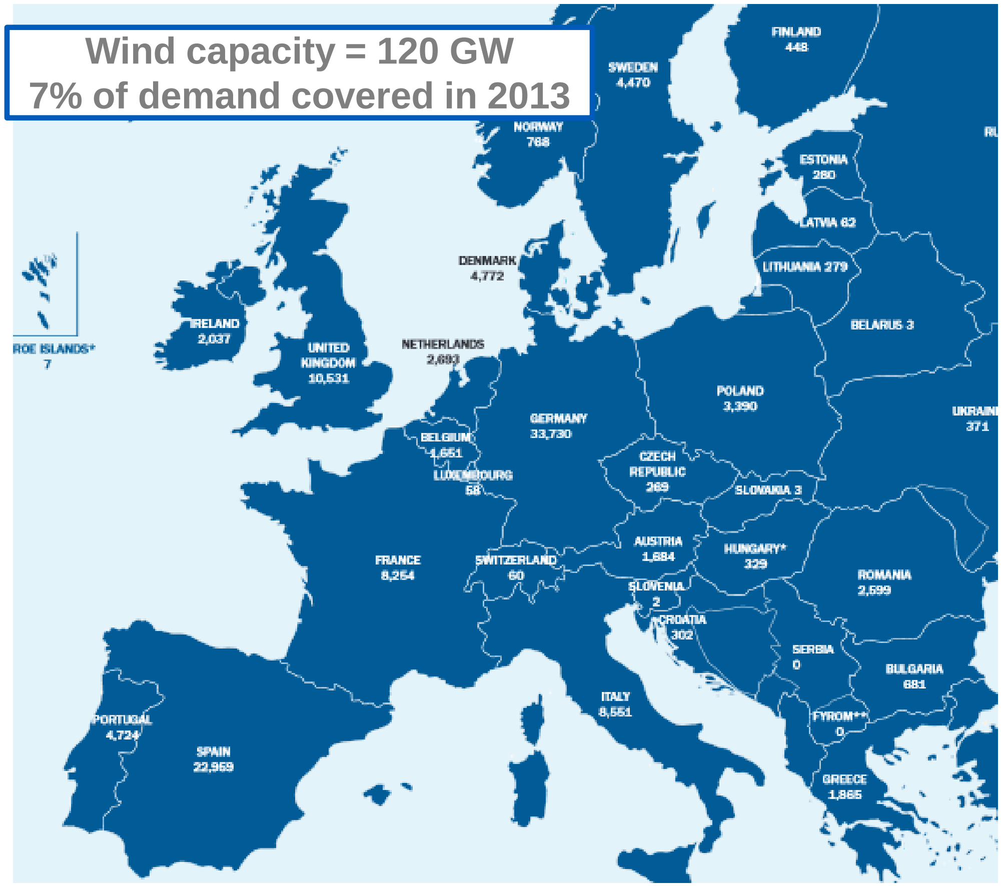
150 PhD students

200 Researchers traching in universities

Research centers around the world

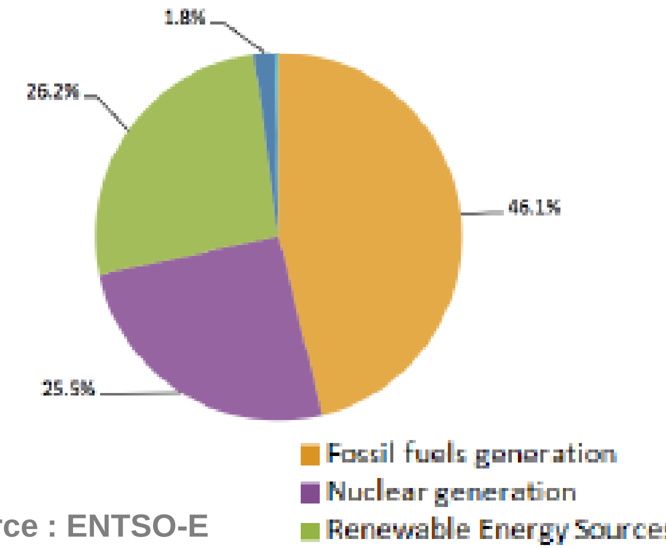
THE EUROPEAN ELECTRICITY SYSTEM AND RES DEVELOPMENT

Wind capacity = 120 GW
7% of demand covered in 2013



PV capacity = 82 GW => 3% of demand covered

Wind + PV= 202 GW in 2013



Source : ENTSO-E

Hydro generation is still the largest RES (Norway, Sweden, Italy, France, Switzerland)

Countries	TSO's	Peak	Capacity	Energy demand	Synchronous systems
34	41	530 GW	930 GW	3340 TWh	5

What is our interest on multi-energy systems analysis

- **Evaluate the impact of energy policies :**
  - Renewable deployment, EU ETS
- **Anticipate evolutions on the energy/electricity demand and adapt business/investment strategies**
- **Analyze business opportunities**
  - Evaluate the benefits of new use of electricity, for the system and for new business development
- **Contribute to the public debate**

THE INTERACTION BETWEEN ENERGY VECTORS NEEDS TO BE TAKEN INTO ACCOUNT WHEN STUDYING THE POWER SYSTEM

Multi-energy planning models

Power system planning and operations models

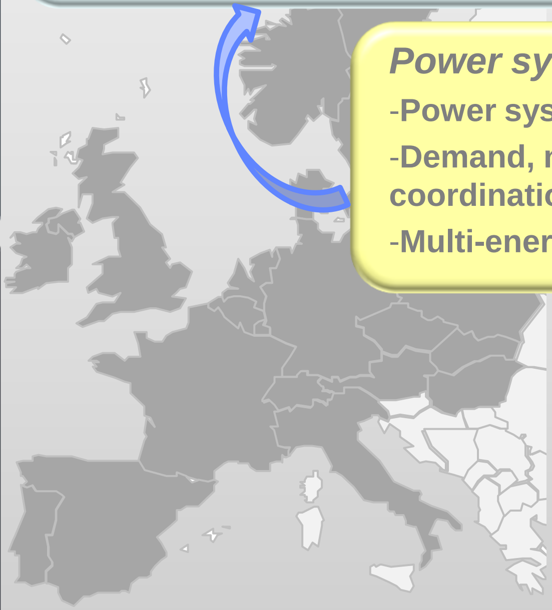
Energy prospective

- Hypothesis on demand, fuel prices, RES potential…

Market design

-Power and gaz market design

-Technical and economical rules



Power system planning

-Power system economic planning

-Demand, network, generation and storage coordination

-Multi-energy usages optimization

Power systems operations

Mid-term	Short term
▪Maintenance ▪Fuels ▪Market coverage	▪Unit commitment ▪Economic dispatch ▪Flexibility and reserves ▪Dynamic stability

OUTLINE

1. **EUROPEAN SYSTEM MODELING AT EDF R&D**

2. **REPRESENTATION OF FLEXIBILITY IN ENERGY MODELS**

   EXAMPLE 1 : USING MULTI-ENERGY SYSTEMS TO EVALUATE ENERGY POLICIES

   EXAMPLE 2 : USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. **REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS**

   EXAMPLE 3 : USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS

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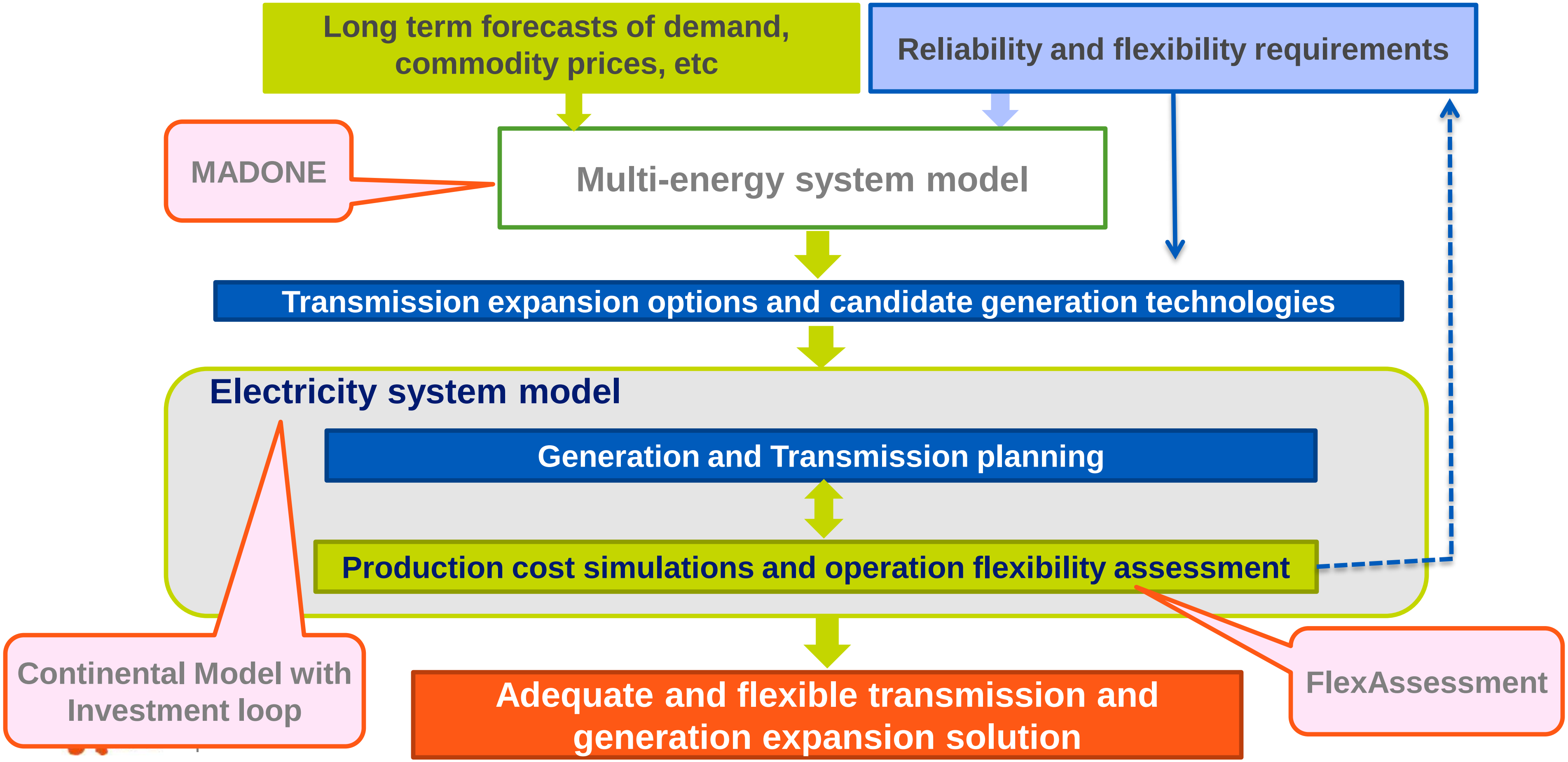
Basic concepts :
What is adequacy ? What is flexibility ?

Adequacy is connected with the issues of **investment decisions** and is used as a measure of **long term ability of a system to match demand and supply with an accepted level of risk.** This is a **measure that internalizes the stochastic fluctuations of the aggregate demand and supply.**

Flexibility is mostly connected with **operation decisions** and represents the ability of a system to **adapt** its to both **predictable** and **unpredictable** fluctuating conditions, either on the **demand** or **generation** side, at different **time scales**, within **economical boundaries**.

INTEGRATION OF THE MULTI-ENERGY VISION IN THE AND ELECTRICITY PLANNING MODELS

Goal: to obtain an a **long term electricity system expansion solution** that ensures a **flexible system** the problem needs to include : 1) the **interaction** between the **energy and the electricity systems** 2) the **long term uncertainties** and 3) the relevant **short term operation constraints** and **uncertainties**



Different approaches to address the integration of energy and electricity systems planning

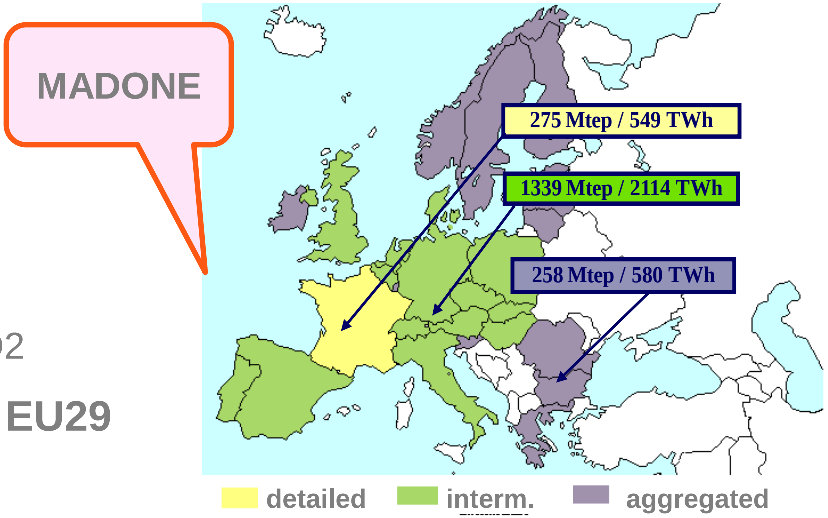
Option 1) Representation of electricity system flexibility in the Times model by increasing the simulation granularity and including additional constraints=> MADONE

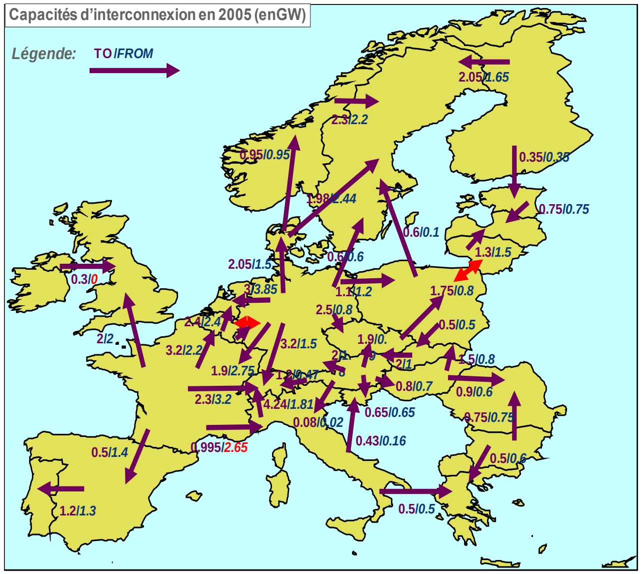
Option 2) Coupling energy system models with electricity system models using a chain of simulation tools with the possibility of back feeding relevant information

- Energy system optimization : Madone
- Electricity system planning : Continental Model with Investment loop
- Detailed near term flexibility assessment : Continental with FlexAssessment

MADONE PERFORMS A MULTI-ANNUAL AND MULTI-ENERGY SIMULATION OF EACH OF THE 29 INTERCONNECTED EUROPEAN COUNTRIES

- **Perimeter EU27+NO+CH (Europe 29)**
  - with different levels of detail depending on the country
- **Trans-national networks represented**
  - electricity and gaz, CO2
- **Storage capacities**
  - hydro (one lake per country + hydro-pumping), gaz, CO2
- **Pipelines/electricity injections at the frontier of EU29**
  - NordStream, Southstream, Nabucco, DESERTEC…
- **National resource potentials & limits**
  - Wind off-shore: km2(depth, wind speed, distance to coast) X Capacity density; Wind on-shore km2 (area potentially available) X Capacity density; solar PV: area available, roofs surfaces; CO2 storage; biomass resources
- **Period and simulation time step**
  - yearly from 2005 to 2010, every 10 years from 2010 to 2050
  - representation of each year with load curves eg: 24, 288 points
- **Outputs**
  - Technology mix & detailed energy balances , energy dependency, and environmental indicators, balance for electricity (including exchanges), association of energy uses and activities….





Continental Model with Investment loop for modeling the European interconnected electricity system

In order to represent a "realistic" European electricity system, we require :

- description of different countries generation mix and key transmission corridors
- interconnection capacities between countries
- management of water reservoirs and pump storage
- demand and variable generation 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 optimization => **stochastic problem**
- **Generation scheduling** needs to be **performed across the whole Europe** including **interconnection** and key transmission constraints **(high performance computing)**
- **Impact of variable generation on static and dynamic security** => **detailed analysis of system operation in the future is needed (hierarchical approaches)**

Continental Model with Investment loop

Continental Model with Investment loop: electricity generation investment model for interconnected systems

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 a price signal that feeds the investment loop

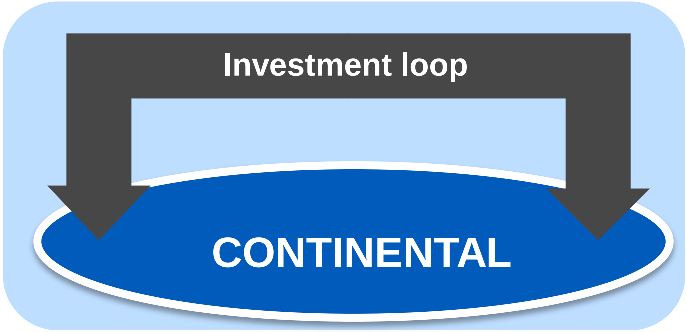
The generation mix needs to respect an adequacy criterion

- Maximum of 3h/year with market clearing price = VOLL

INPUT DATA

Demand
Variable generation profiles
Interconnection constraints

Storage
Investment costs
Commodity prices
CO_2 price



OUTPUT

Optimal thermal generation mix
Production dispatch
Production costs

Market clearing prices
CO_2 emissions
Hydro stock level paths
Interconnection uses

CONTINENTAL MODEL HYDRO-THERMAL GENERATION SCHEDULING

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

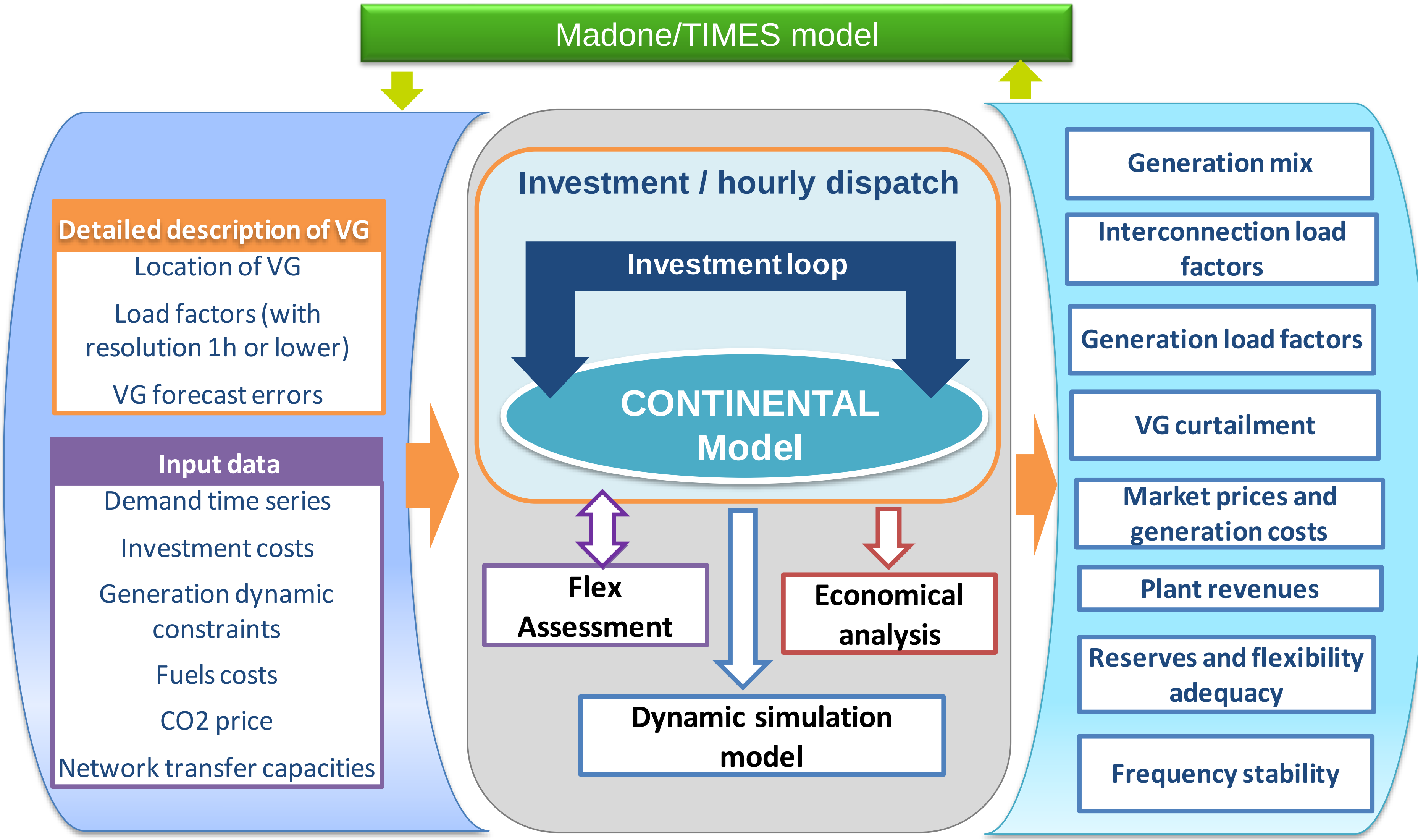
Constraints include primary, secondary and tertiary reserve and generation dynamic ratings

Multi area optimization with interconnection constraints represented by NTC

For each dispatch period and for each zone the dispatch solution and the market clearing prices are obtained to access the revenues of generation units

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

Chain of simulation tools for detailed flexibility assessment of Continental model scheduling solutions



The model coupling can include multi-annual investment trajectories simulated with Times complemented with annual snapshot simulations with Continental Model

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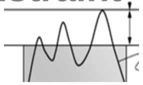
REPRESENTATION OF FLEXIBILITY IN THE ENERGY MODEL : COMPARISON MADONE-CONTINENTAL

MADONE

- **Bottom-up TIMES model : all 29 interconnected European countries**
- **Renewables national resources potentials & limits detailed:** Wind off-shore, wind on-shore, roof for PV etc…
- **Horizon = 2005 to 2050 with a perfect foresight of each year**
- **Time-slices: 24 or 288**
  - 24 =Peak and Off-Peak for each month
  - 288 = 2 representative day (Week/W-E, bi-hourly)/month
- **Peak equation:** **~~additional~~ demand constraint**

$$Dem_{\max}(t) - Dem(t)$$



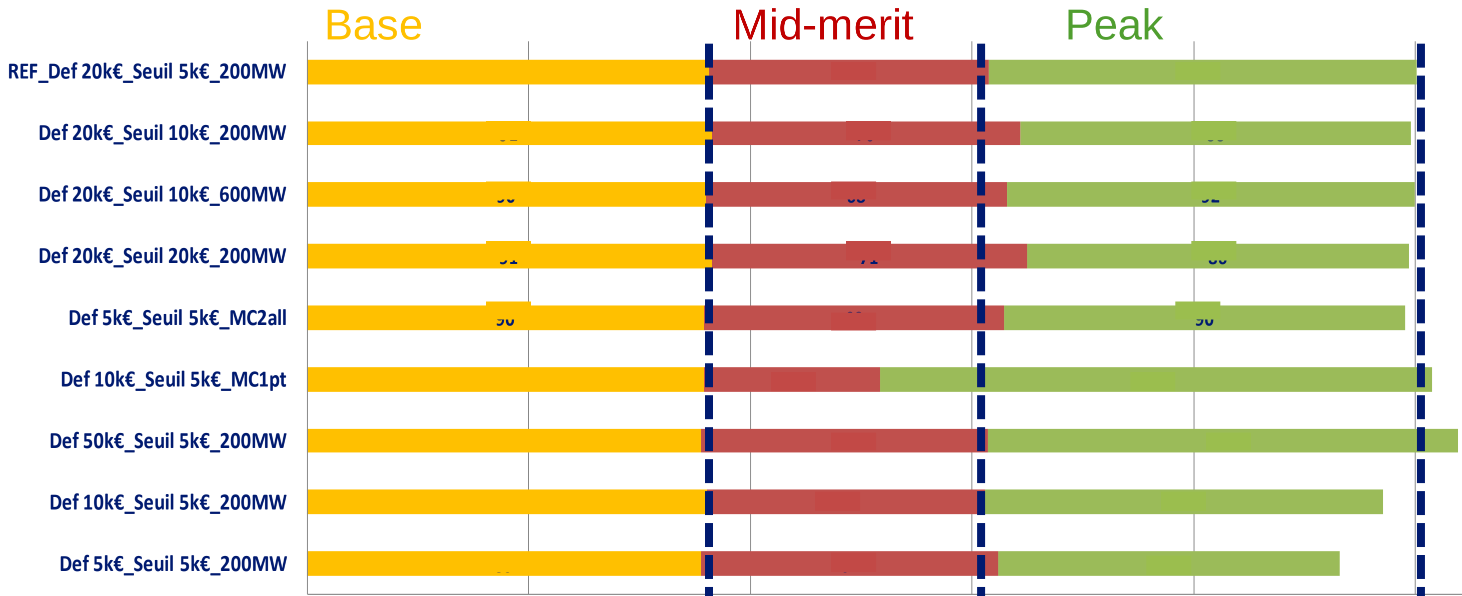
  - **With or without** renewable contribution
- **Deterministic**
  - Or multi-scenarios for one chosen year : testing with 4 annual scenarios

Continental Model with Investment loop

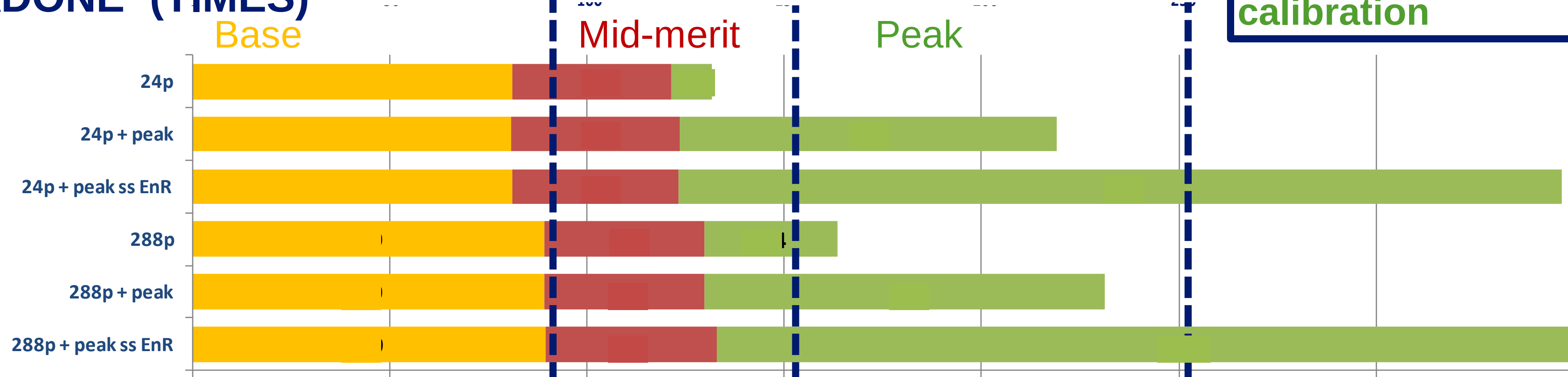
- **EDF R&D's Elec Production Cost model**
- **Electricity generation portfolio optimization**
- **Stochastic simulation of hourly system operation**
  - Demand-generation balancing solved for one year with hourly resolution
  - Interconnection constraints included
  - Stochastic parameters: (T°, hydro, wind, PV and generation outages)

COMPARISON OF CONTINENTAL AND MADONE OPTIMAL THERMAL GENERATION MIX

CONTINENTAL



MADONE (TIMES)



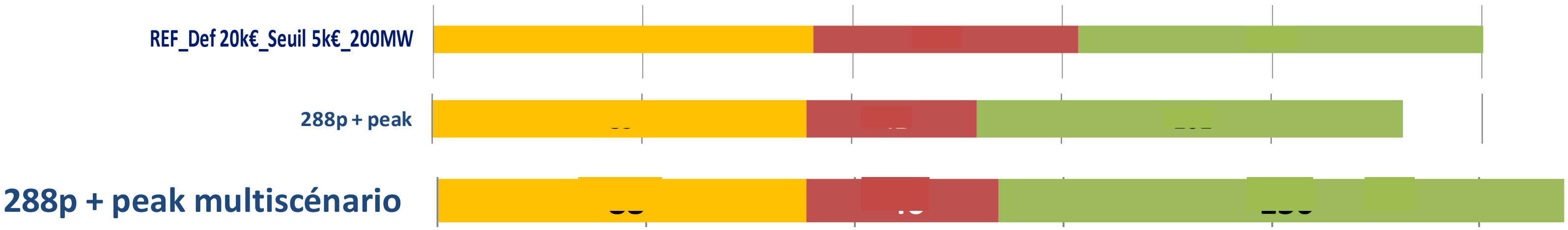
- Consistency of base capacity needs between the 2 models

- **Mid-base capacity underestimated with TIMES model**

- **Peak capacity dependant on peak equation calibration**

MULTI SCENARIOS SIMULATIONS

- **In the tests we made, a multi scenario approach helps reducing the gap for mid-merit capacity but leads to a larger over-estimation of peak capacity**
  - Choice of a (limited =4) set of scenario: how to select the right ones?
  - Calibration of peak equation could be a solution… but largely dependent on the system studied



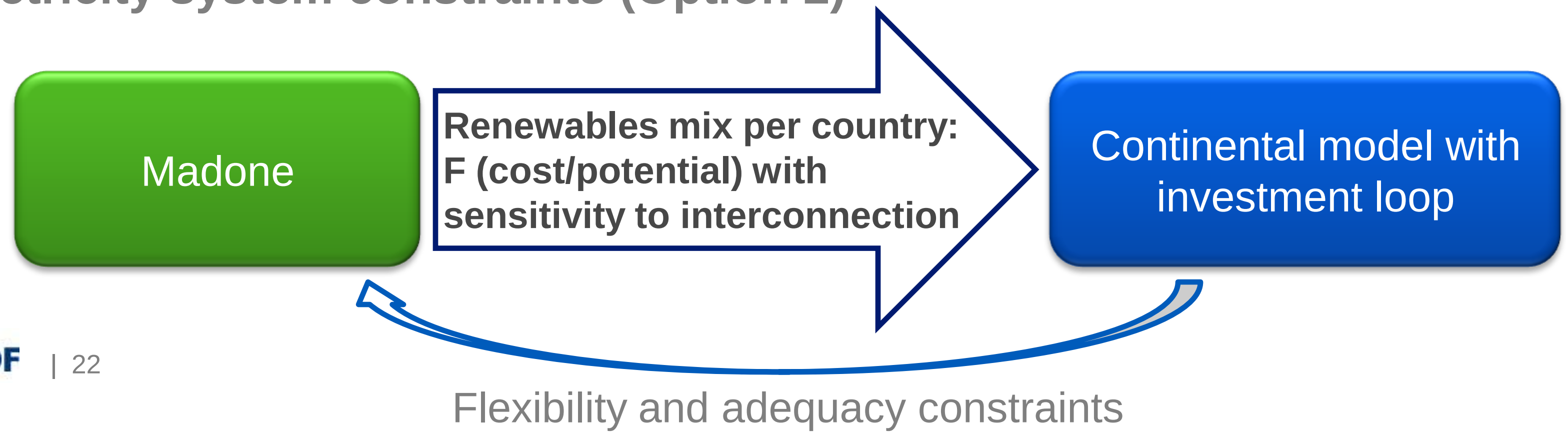
Madone is suitable to provide a "merit order" between technologies including the mix and geographic distribution of renewables

- **Representing explicitly dynamic constraints in a long-term TIMES large planning model doesn't seem realistic for the time being**

- **Without modeling operation margin and reserve requirements & dynamic constraints the generation dispatch is not accurate**
  - For instance, a peak equation imposes investment in back-up capacity, not its use.

- **… but the objective is to have the « right » merit order between technologies investment decisions,**
  - « right »= least cost + meeting capacity adequacy & flexibility adequacy system requirements

- **And then to assess, ex-post, if the generation mix calculated meets the electricity system constraints (Option 2)**



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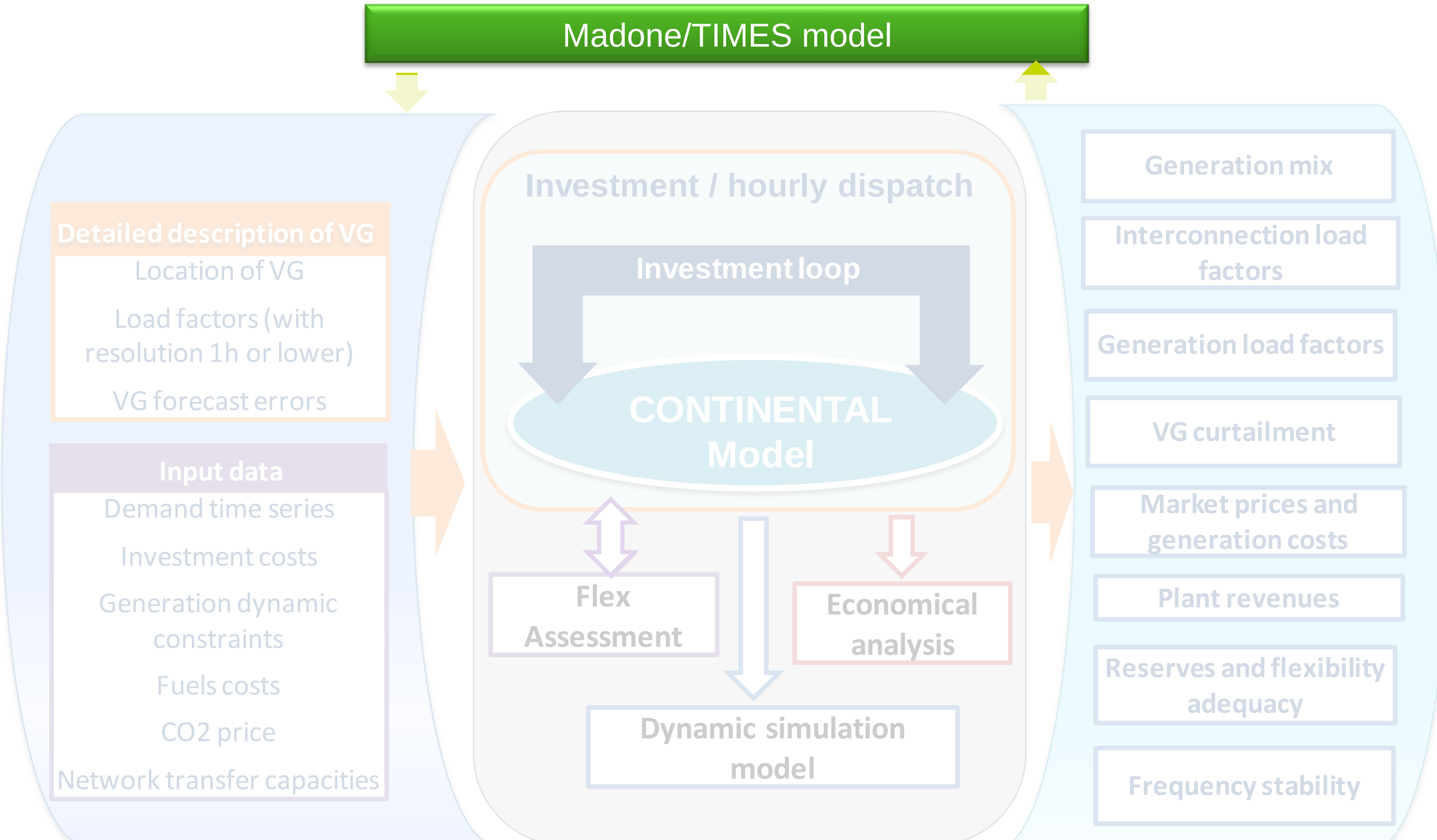
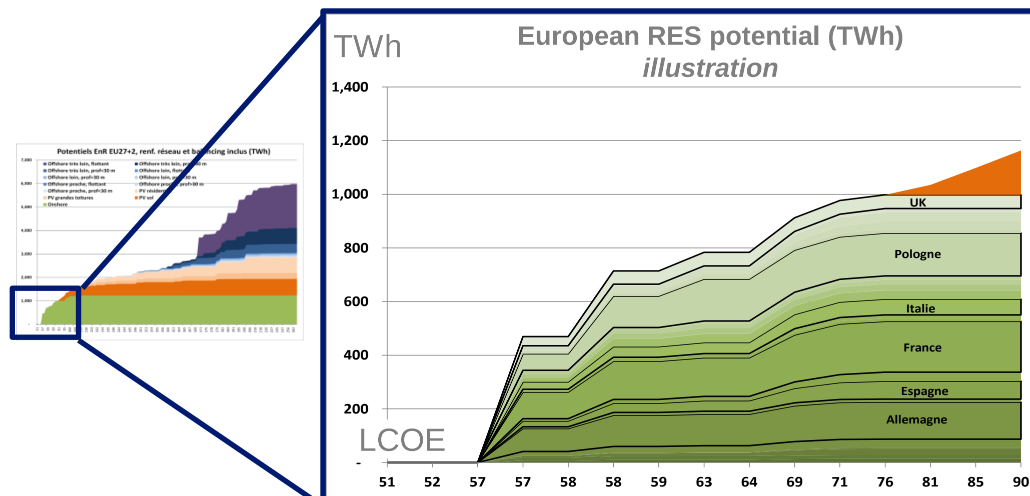
Chain of simulation tools for detailed flexibility assessment of continental model scheduling solutions



Analyze the decarbonization path of the European power system taking into account CO2 constraints

- **European decarbonization targets from the energy system determine the volume of EU ETS permits allowed**
  - **-43 % in 2030**/2005 (EU31): **this constraint applies for an aggregated level for several years** (« **banking** » allows to store from one year to the next)
  - **Market Stability Reserve** after 2019
- **This interacts with the RES targets**
  - **27% RES of the energy consumption in 2030** (EU28), and NREAP à 2020
  - implies 45% RES in power generation, **27% wind and solar**
  - assuming a reduction of RES costs
  - and large RES potential

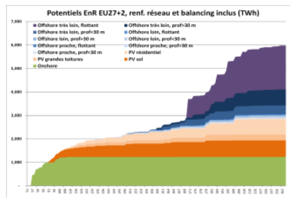


This simplified approach takes into account the inter-annual trajectory from 2013 to 2030

Input data

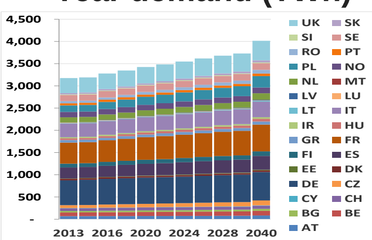
CAPEX, OPEX, life expectancy, efficiency and emission factors

PV and wind potential (R&D MFEE)



Fuel costs

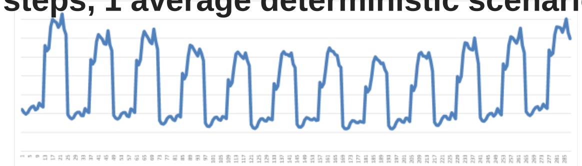
Year demand (TWh)



CO2 emissions authorized

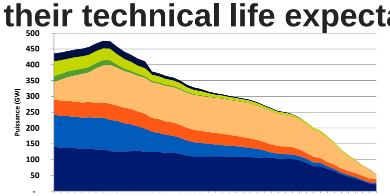
System costs minimization over the period 2013-2030+

Load and RES generation curve (288 time steps, 1 average deterministic scenario)



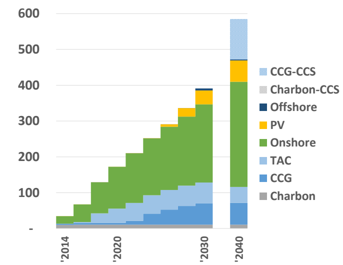
NTC

Retirement of thermal units according to their technical life expectancy

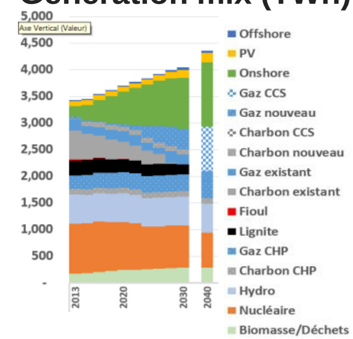


Results

New installed capacities (GW)



Generation mix (TWh)



RES

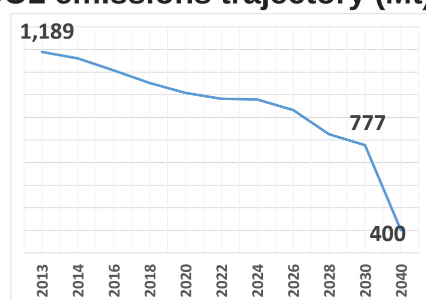
Thermal

COHERENCE

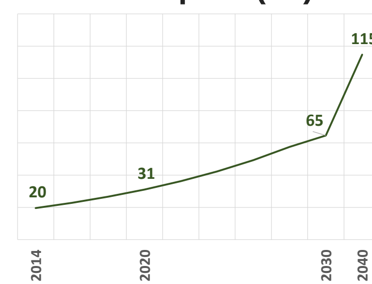
CO2 emi

CO2 price

CO2 emissions trajectory (Mt)



CO2 price(€/t)



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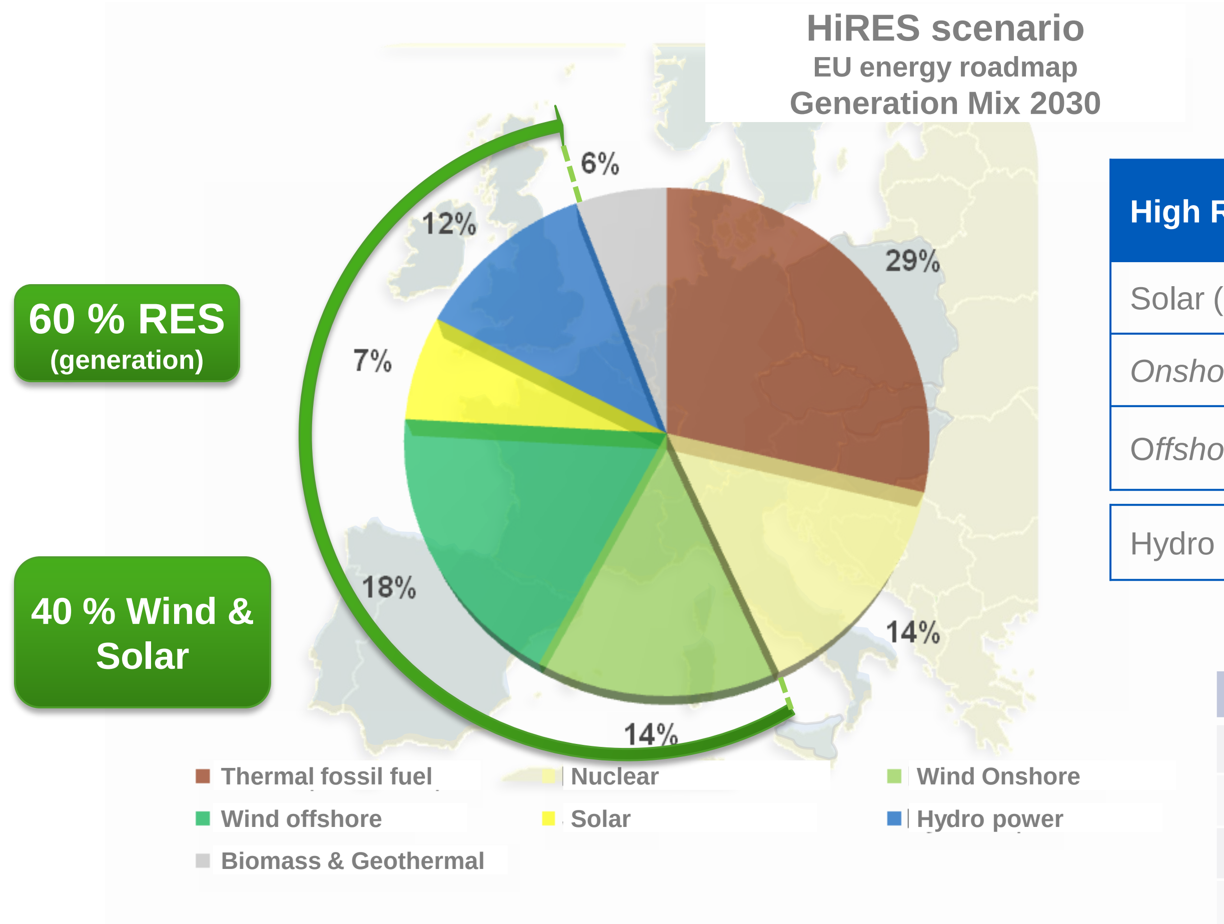
Simulation of the EU Energy Roadmap « HiRES 2030 » scenario



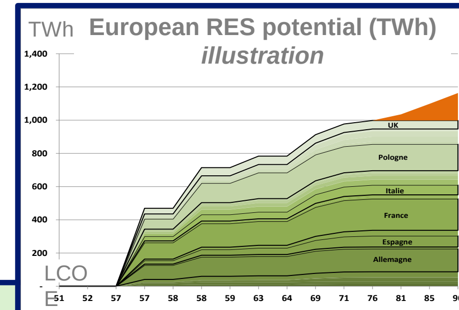
High RES 2030	GW	Load factor (h/yr)
Solar (PV)	220	1100
Onshore wind	280	1900
Offshore wind	205	3200
Hydro	120	3800

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

A simplified approach to place RES generation across Europe

Wind and solar energy targets 2030

TIMES élec
Builds the RES mix and optimize the location



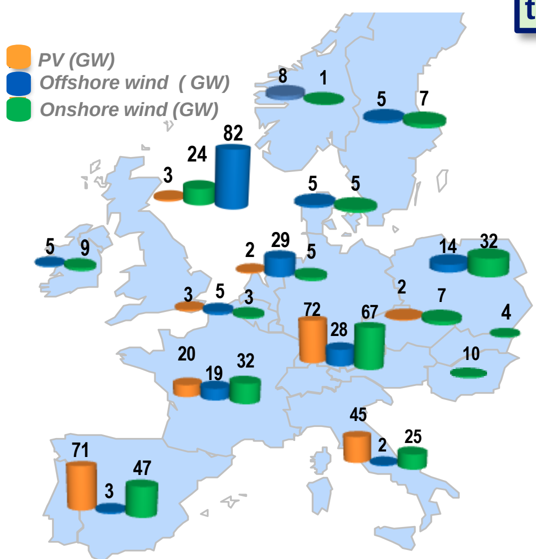
Describe the power system :
- Thermal and renewable remaining units
- Interconnections
- Technical and economical caracteristics.

Precise RES hypothesis :
- New turbines V112 & V126 taken into account when calculating the load factor

Max density for wind onshore development constraints

Installable yearly capacity limits for every technology

RES geographical distribution



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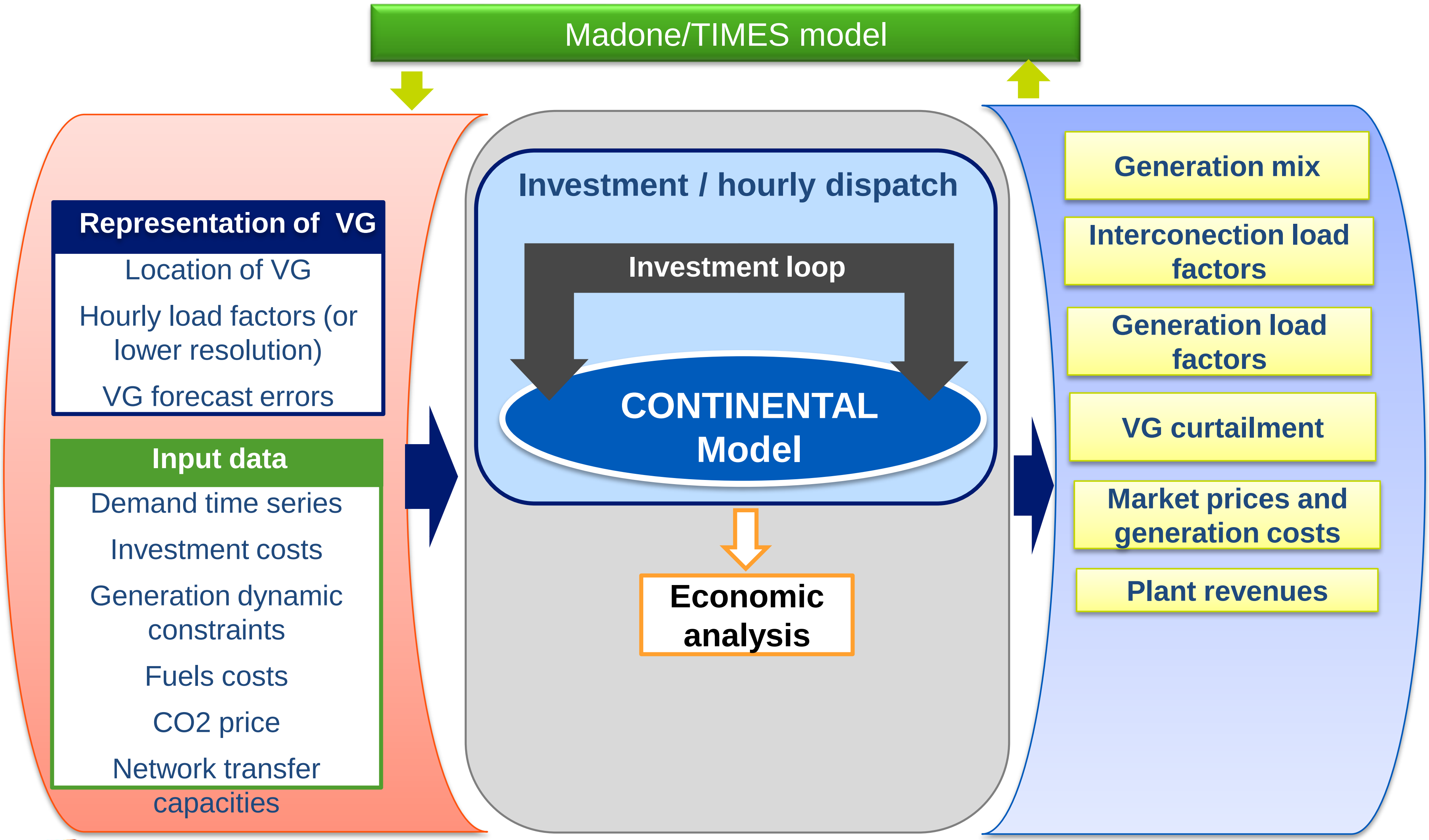

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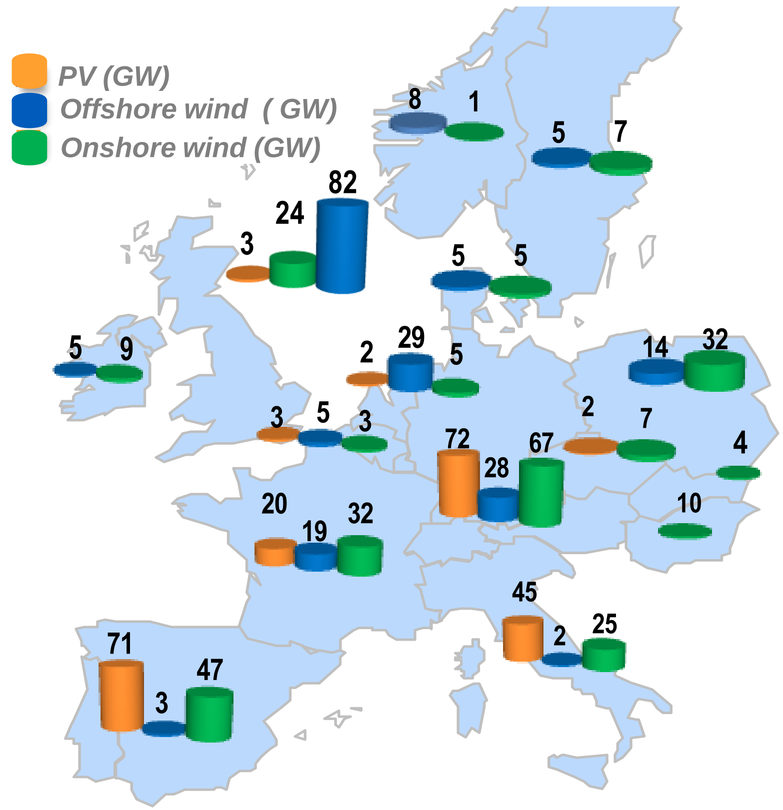
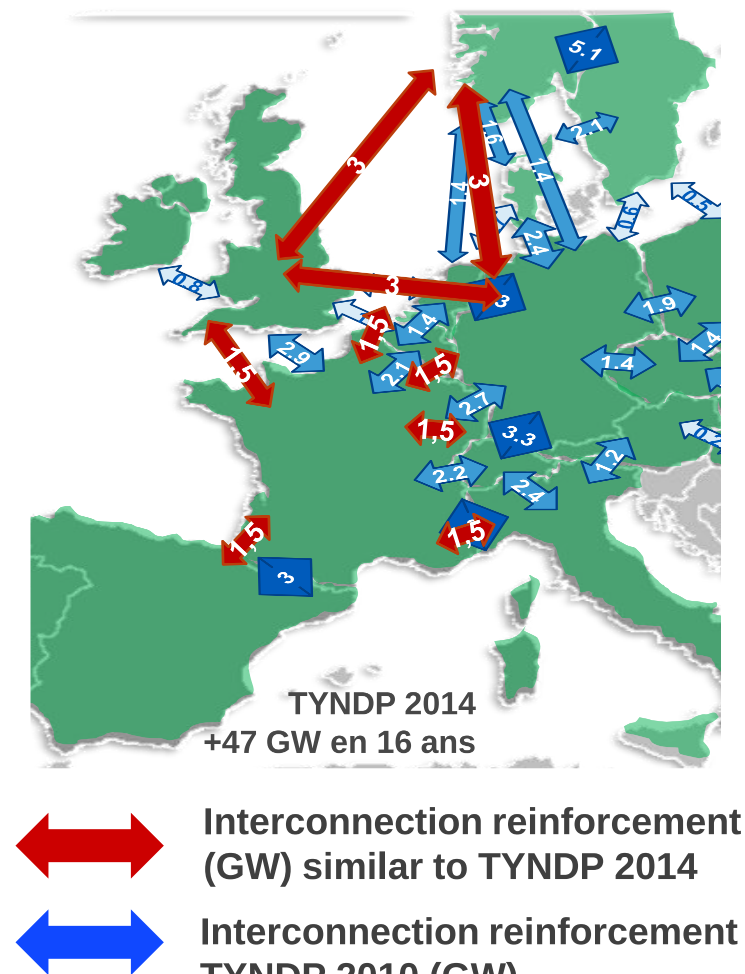
Where to integrate large share of renewables with network constraints ?

RES geographical distribution



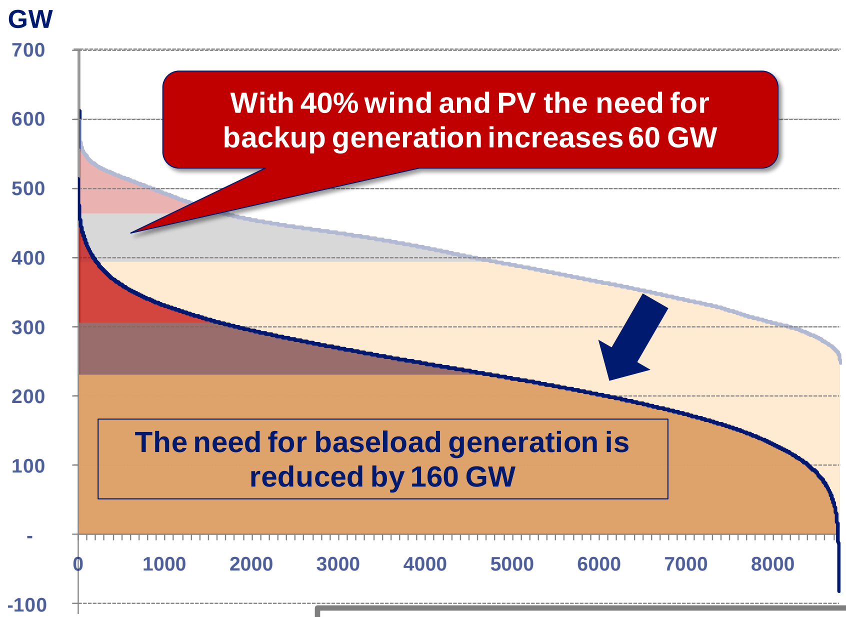
Network development scenario

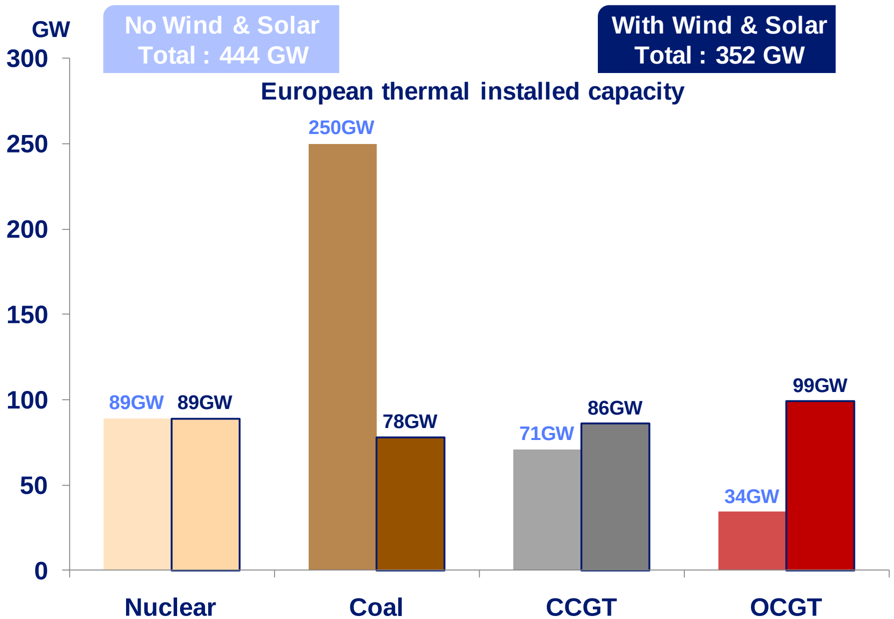


Interconnection reinforcement (GW) similar to TYNDP 2014

Interconnection reinforcement TYNDP 2010 (GW)

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 decarbonization can only be achieved with a significant share of carbon free base load, in particular nuclear

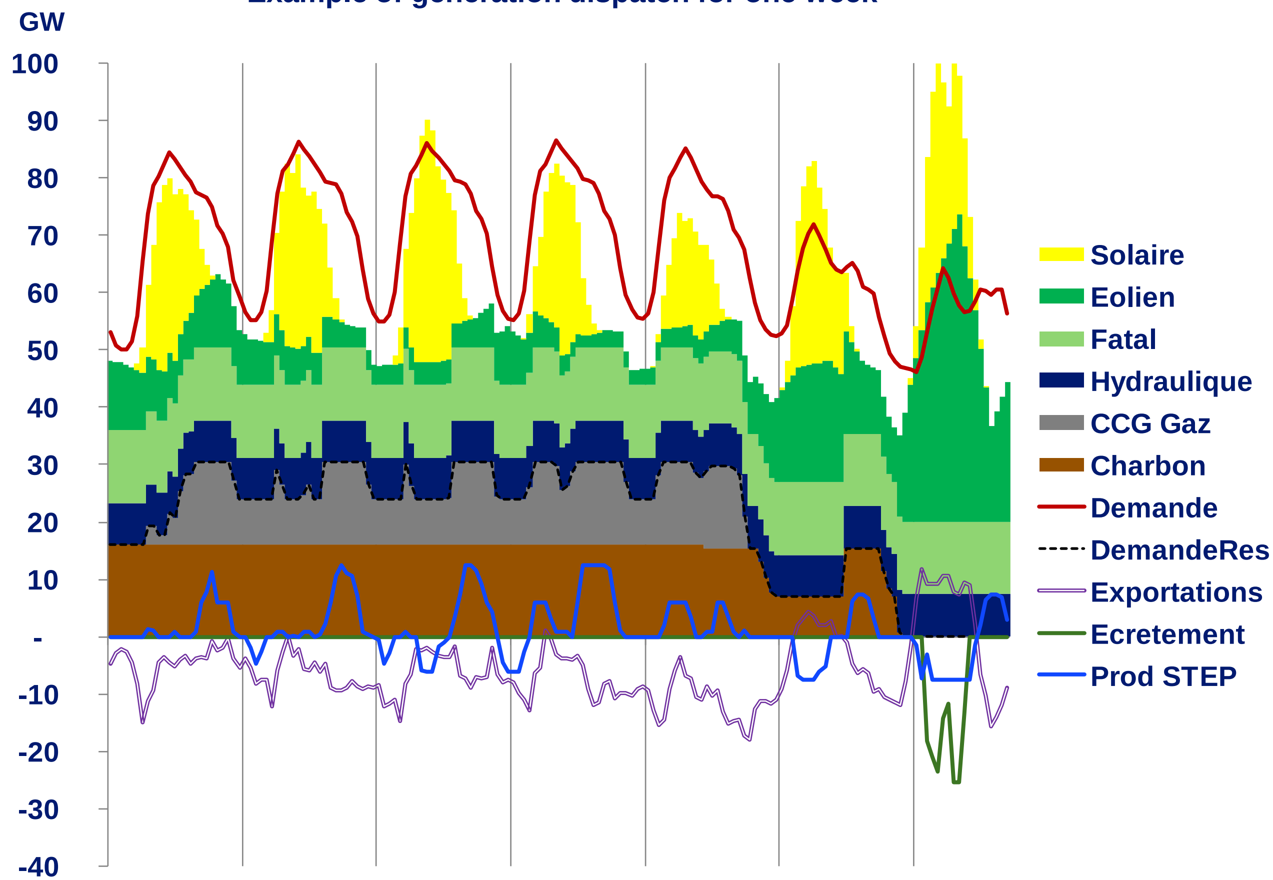
Flexibility sources and wind curtailment help to balance generation and demand

Wind and PV generation lead to a more variable net demand

Interconnections, storage and wind curtailment help to smooth the demand addressed to conventional generation

Conventional generation flexibility is used to follow the remaining variability

Example of generation dispatch for one week



- Wind curtailment is inevitable when must run generation plus variable generation exceed demand.
- In some cases wind curtailment is also used for economic reasons (cheaper than start and stops of conventional plants)

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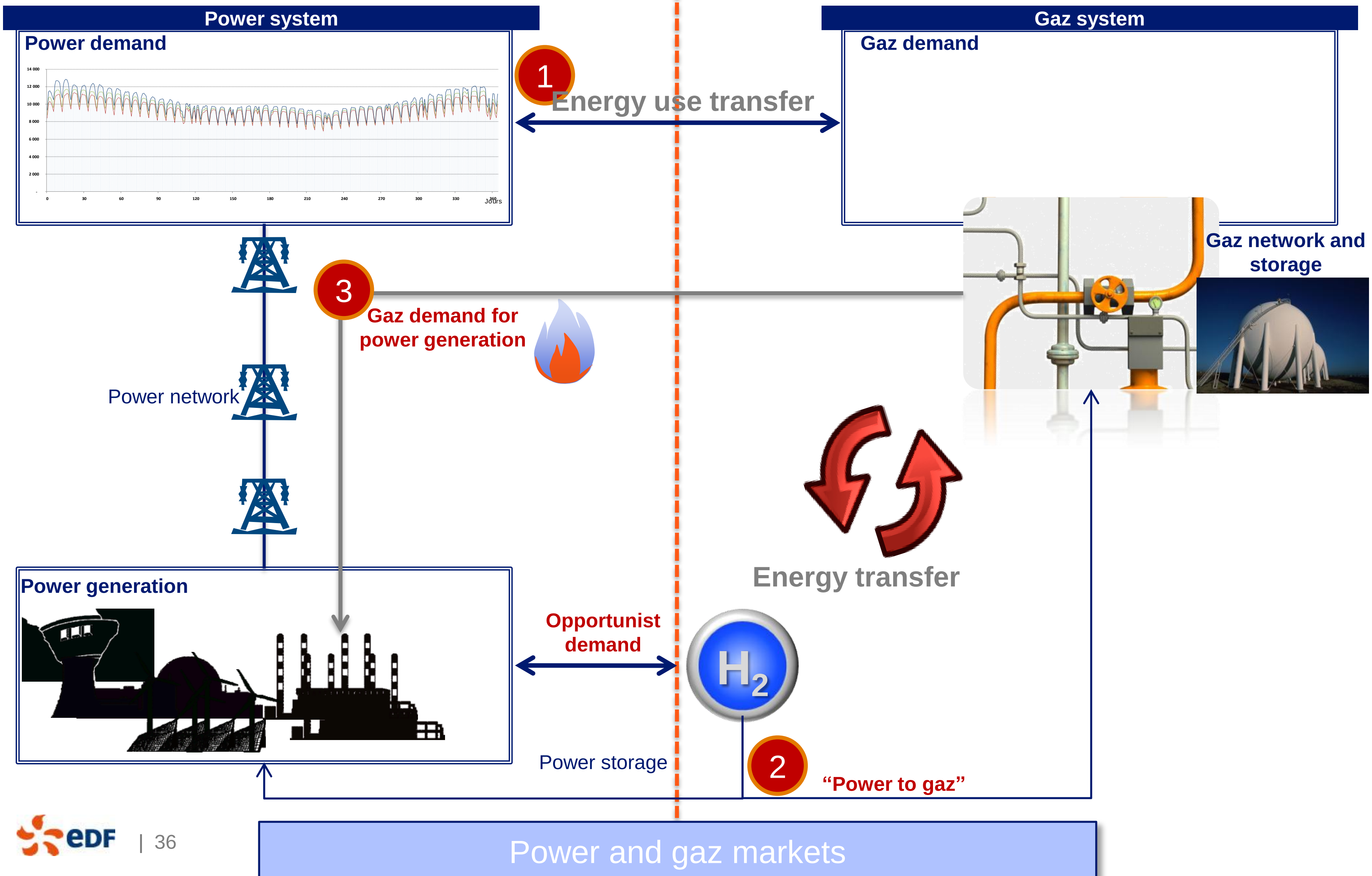
   EXAMPLE 2 : USING MULTI-ENERGY SYSTEMS TO DEFINE INPUTS FOR AN HOURLY DISPATCH MODEL

3. **REPRESENTATION OF FLEXIBILITY IN POWER DISPATCH MODELS**

   EXAMPLE 3 : USING POWER DISPATCH MODELS TO EVALUATE MULTI-ENERGY SOLUTIONS

HYDROGEN COUPLES POWER AND GAZ SYSTEMS WHEN TRANSFORMED IN CH_4 COMBINED WITH CO_2



THE VITESSE² PROJECT EXAMINE THE TECHNO-ECONOMIC RELEVANCE OF METHANOL PRODUCTION, FROM CO2 EMISSIONS AND HYDROGEN

- **In the future, the importance of hydrogen as an energy carrier could grow as it is a chemical intermediary with multiple applications.**
- **The present study examines how adding the flexible demand of the electrolyzers in France would impact the European power system while keeping the cost of hydrogen production close to competitiveness.**
  - Renewable energy development (mainly photovoltaic and wind energies) is one of the means to decarbonize the European energy system : flexible electrolyzers could help managing the power system and reducing curtailment
  - It could be a way to mitigate CO2 emissions if combined with CO2 to produce methanol.

This power system approach enables to perform a cost-benefit analysis of using electricity for some new use

Electrolysis

Power generation

?

Reforming

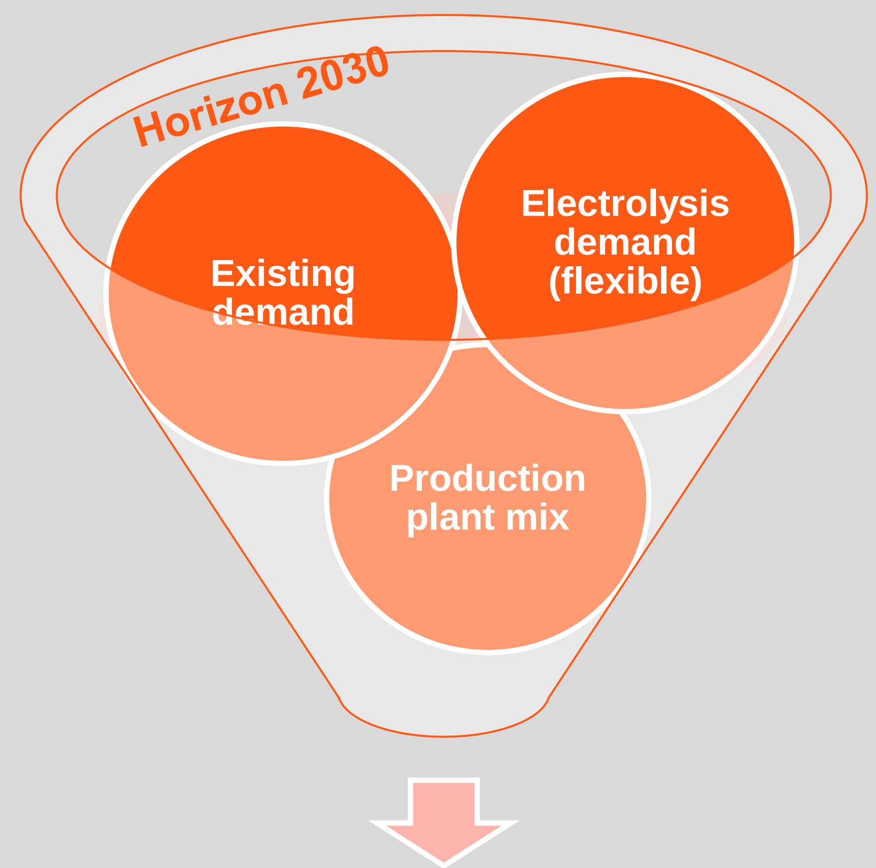
H_2

CH4 + H2O ⇌ CO + 3 H2
CO + H2O ⇌ CO2 + H2

H_2 Cost

CO_2 emissions

METHODOLOGY:
USING AN HOURLY LONG TERM ECONOMIC DISPATCH MODEL



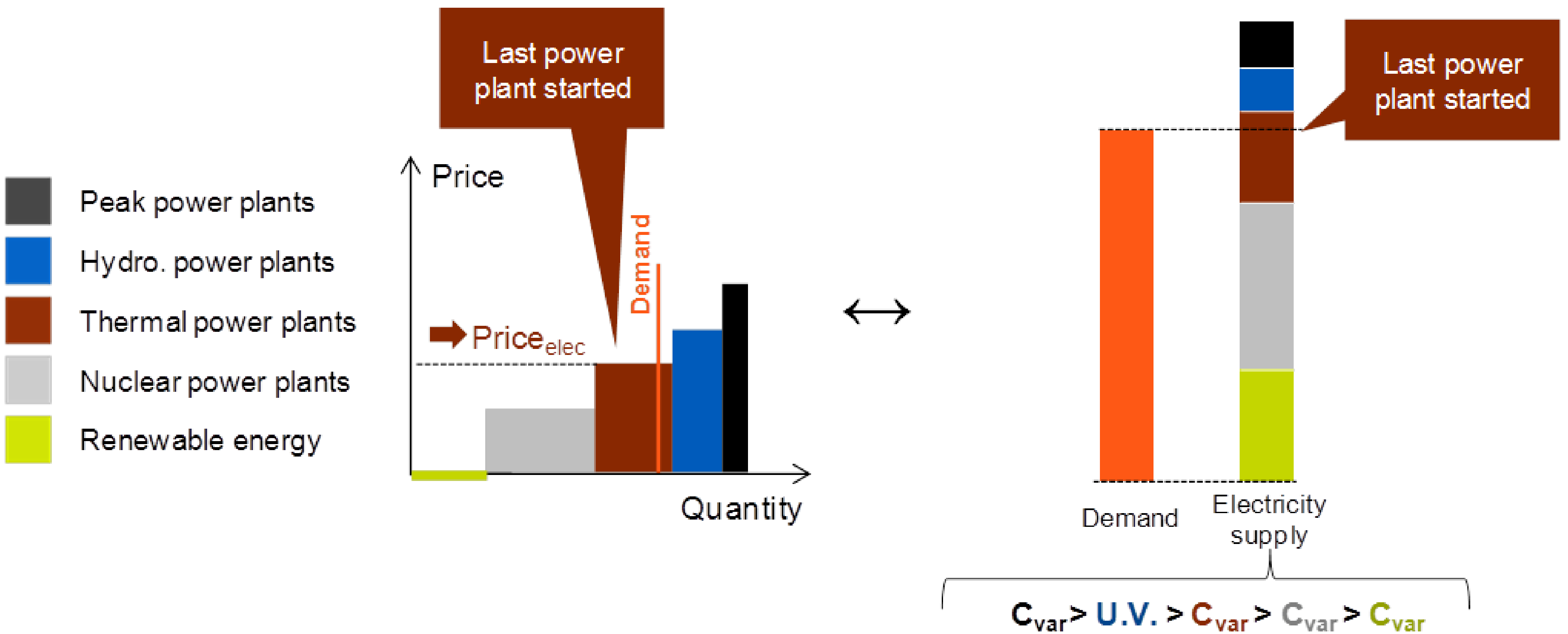
- Power plant production planning
- Electrolysis demand positioning through system cost minimization
- Electricity marginal cost

Non-marginal approach: influence of electrolysis system penetration on marginal costs

Assumption: marginal cost ~ electricity spot price

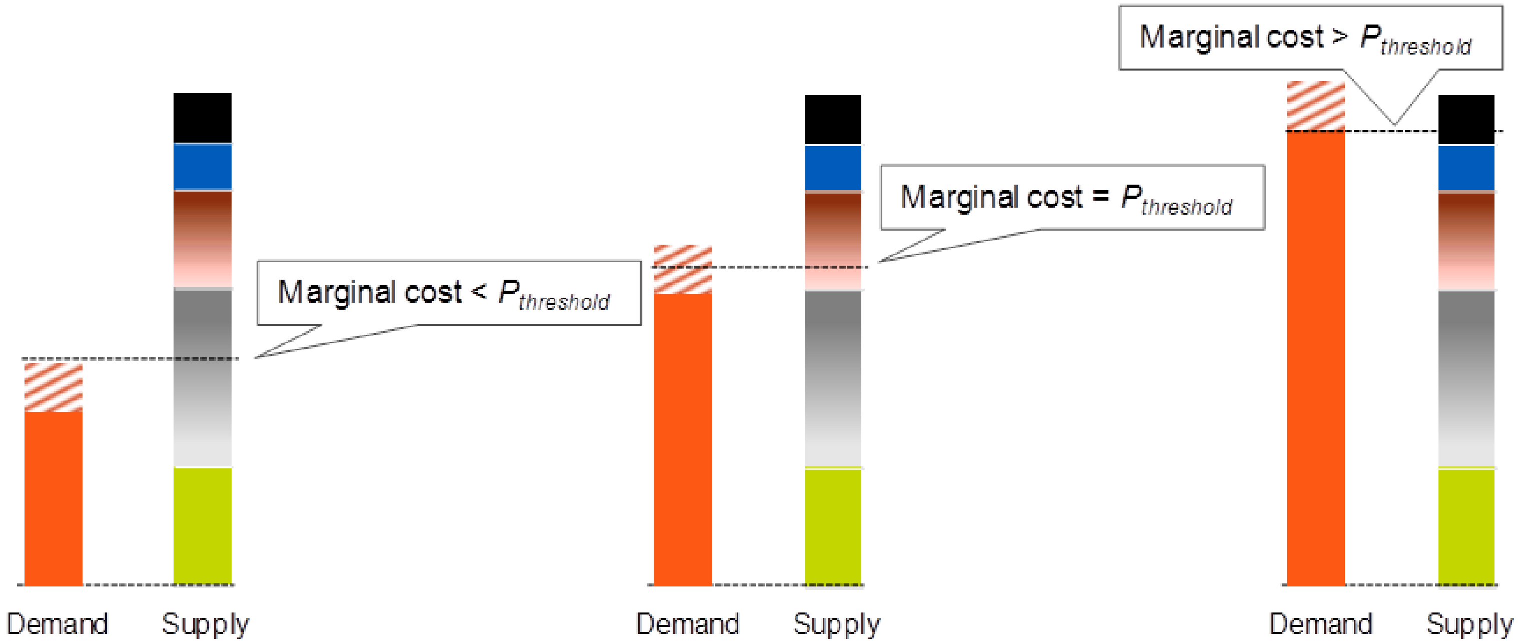
MARGINAL COST FORMATION

- **Power plants start-up: merit order according to the variable costs**
- **Market price ~ marginal cost of the electricity area (i.e. France)**



ELECTROLYZER OPERATION: SELECTION OF A THRESHOLD PRICE

- **Hydrogen production: additional electricity demand which is satisfied while not exceeding a threshold price**



Situation #1

The flexible demand is completely met

Situation #2

The flexible demand is partly met

Situation #3

The flexible demand is not met at all

TWO PROSPECTIVE SCENARIOS: MEDIAN AND RUPTURE

- **Time horizon: 2030**
- **Scenarios for France; simulation of the whole European system**
- **Median scenario: business-as-usual; in line with the French TSO assumptions**
  - Nuclear power: 56 GW (- 7.1 compared to current situation)
  - Renewables: +99 TWh compared to current situation
- **Rupture scenario: very voluntaristic; based on the EU "HighRES" scenario**
  - Renewables: +47% compared to the median scenario
  - Nuclear power: 65 GW (slightly higher than current situation)
  - Also: high level of interconnections

EVALUATING THE CARBON IMPACT OF FLEXIBLE HYDROGEN PRODUCTION IMPLEMENTATION

- **Not exactly a hydrogen carbon content**
- **Rather a carbon impact of flexible hydrogen production implementation**

- **Marginal approach:**

comparison of the CO_2 emission level of the European power system between
  - the reference case: no additional demand

  and
  - the hydrogen implementation case: including the electrolysis unit demand

EVALUATING THE ECONOMIC COMPETITIVENESS OF FLEXIBLE HYDROGEN PRODUCTION IMPLEMENTATION

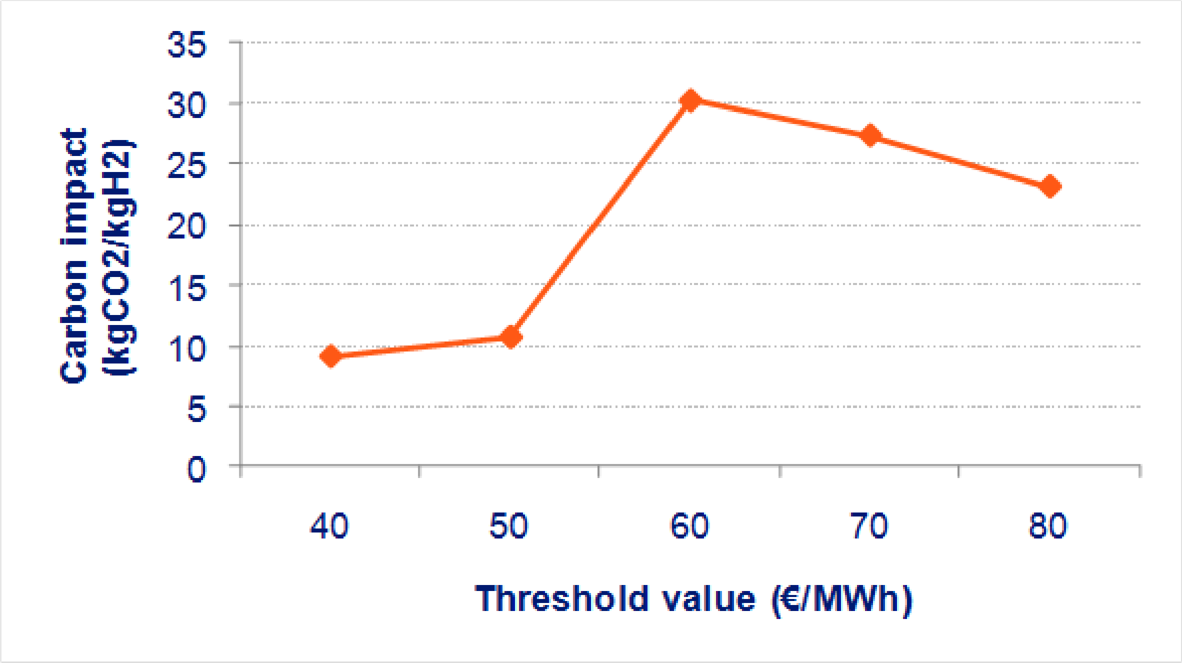
- **Assessment of the levelized hydrogen production cost, including:**
  - The investment annuity
  - The electricity consumption cost
  - Other O&M expenses

- **The electricity consumption and annual hydrogen production depend on:**
  - the threshold price
  - the selected scenario

- **The electricity consumption cost is built with the electricity marginal cost**

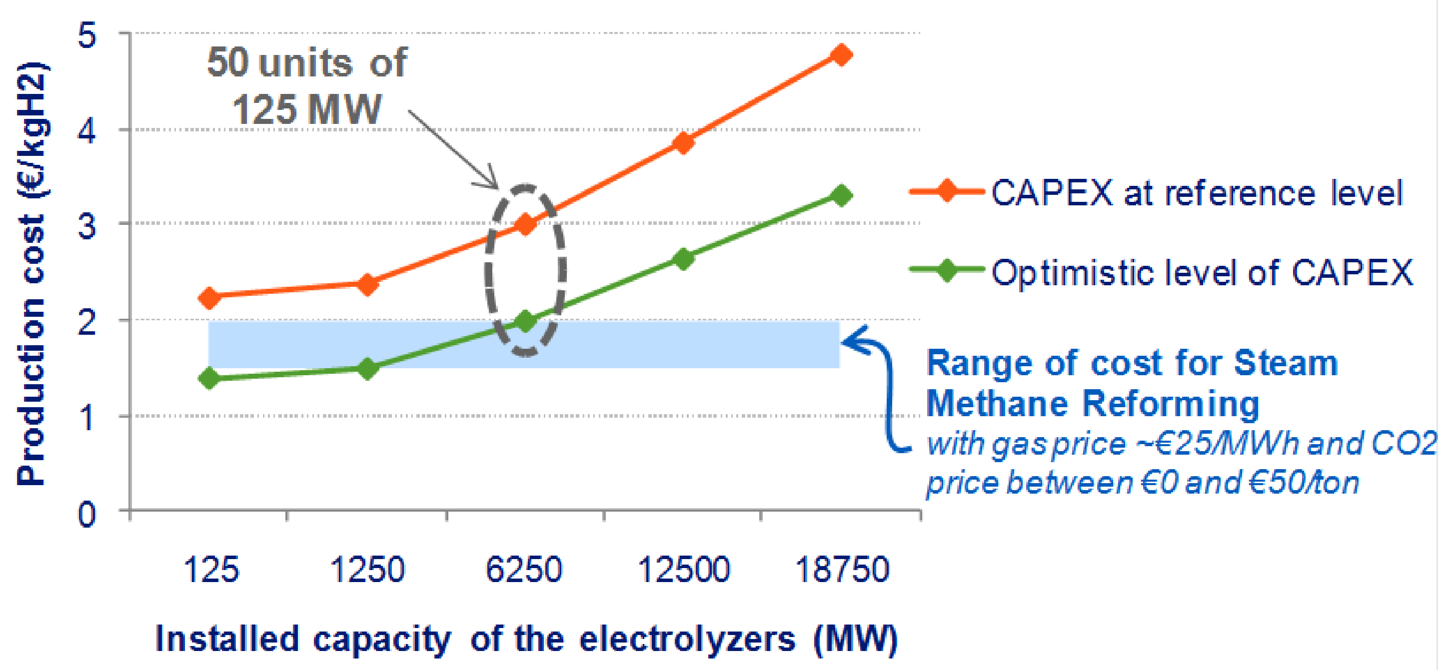
RESULTS:
NO OPPORTUNITY IN THE MEDIAN SCENARIO

- High carbon impact



RESULTS:
IMPLEMENTING UP TO 50 ELECTROLYSIS UNITS IN THE RUPTURE SCENARIO

- **Annual production: 500,000 tons**
- **Carbon impact: < 4 kg_{CO2}/kg_{H2}**
- **Production cost: as low as €2-3 / kg_{H2}, depending on the capex level**



CONCLUSION

- **Flexible production: an opportunity to reduce hydrogen production costs**
  - Take advantage from low-cost low-carbon electricity

- **Due to high investment costs it has to be used frequently to build a credible business case**
  - Opportunity only in the framework of very proactive scenarios with high penetration rates of low-carbon energy → beyond 2030
  - In such scenarios: competition with any kind of flexible electric demand (storage, etc.)

TO FIND MORE…

- G. Prime, V. Silva, J. M. Schertzer, M. Lopez-Botet Zulueta, Integration of flexibility assessment to generation planning of large interconnected systems, submitted for publication to IEEE Transactions on Power Systems.

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

- Pauline Caumon, Miguel Lopez-Botet Zulueta, Jérémy Louyrette, Sandrine Albou, Cyril Bourasseau, Christine Mansilla, Flexible hydrogen production implementation in the French power system: Expected impacts at the French and European levels, Energy, Volume 81, 1 March 2015, Pages 556-562, ISSN 0360-5442

- Vera Silva, Alain Burtin, Technical and economic issues of the integration of a large share of variable RES to the European Interconnected systems, Public communication of EDF R&D, 17 of June 2015, available from: http://chercheurs.edf.com/programmes-de-recherche/environnement-et-energies-renouvelables/analyse-technique-et-economique-du-systeme-electrique-europeen-avec-60-d-energie-renouvelable-295308.html&return=40529

APPENDIX

Electricity system functions and flexibility

	Time scale	Domain	Elements affected	Flexibility sources
Close to real time horizon	Seconds	Frequency regulation: Frequency containment reserves (FCR)	Dynamic frequency stability	FCR reserve providers
	Minutes	Frequency regulation: Frequency restoration reserves (FRR)	Frequency	FRR reserve providers
Scheduling and dispatch horizon	Minutes to hour	Replacement reserves (RR) and balancing Economic dispatch	Follow net load variation and FCR and FRR	Observability and Forecasting Increase reserves Ramping capability Quick start plant
	Hours to days	Generation scheduling Day-ahead and intra-day markets	Generation dispatch Transmission and distribution operation Wind utilisation	Observability and Forecasting Efficient market design Scheduling flexibility
Planning horizon	Years	Expansion planning	Generation adequacy Flexibility adequacy Transmission and distribution reinforcement	Optimise generation mix Coordination between generation and network investment

MADONE: a bottom-up TIMES model

PRIMARY ENERGY

Uranium supply

Oil & solid fuel supply

Gas supply (Eurasian area)
- Native gas production
- Pipeline transportation
- Gas storage
- LNG

Biomass-waste supply
- Primary ressources (17 types)
- Conversion technologies (13)
- Final bio-energy products (7)

Wind, solar, hydro supply
- availabilty factors (country + on/off shore + wind speed (9) + hours differenciation)
- **Ressources limits**: areas X capacity density hyp.
Ex: wind off –shore: km2 available per country according to wind speed (9), distance to coast (2) and depth (3)
Ex: solar PV: m2 of roofs available, land available…

CO2 storage potentials:
Saline aquifers, DGOF on & off-shore

(efficiency rates of direct consumption processes)

TRANSFORMATION PROCESSES

Electricty & steam production:
- >50 power generation technos
- Cogeneration: 21 technos
- District heating: 7 technos
- Industrial boilers
- Interconnections among countries

Refineries

Industrial transformations

FINAL ENERGY

Industry:
- 18 main sectors
- 47 sub-sectors
- 53 energy using technos.

Residential sectors:
- 8 types of dwelling
- 11 energy needs (heating, HW, cook., light…)
- 11heating+hot water technologies
- 3 cooking technos
- 16 other electric appliances

Service sectors:
- 7 main sectors
- 2 types of dwelling for each sector
- 7 energy needs (heating, HW, light, computers…)
- 6 heating+HW technos

Transport sectors:
- Passengers and freight
- 9 transports modes
- 23 transport means

Agriculture:
- 6 energy uses

Non energy uses:
- 6 energy uses

Energy sector consumption:
- Grid losses, ancillary conso etc.
= linked to production

VITESSE PROJECT - FLEXIBLE HYDROGEN PRODUCTION: ALKALINE ELECTROLYSIS

- **Technical characteristics**
  - Unit size: 125 MW
  - Power consumption: 47.9 kWh/kg_{H2} (constant)
  - No dynamic constraint

- **Economic data**
  - Capex:
    - Reference: €1200/kW (150 M€ per electrolysis unit)
    - "Optimistic": €636/kW
  - Plant life: 30 years
  - Electrolyzer replacement after 15 years
  - Maintenance: 2%/year of the capex
  - Discount rate: 8%