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Power Systems, Flexibility and AI: Managing the New Rhythms of the Grid

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CORIOLIS Conference

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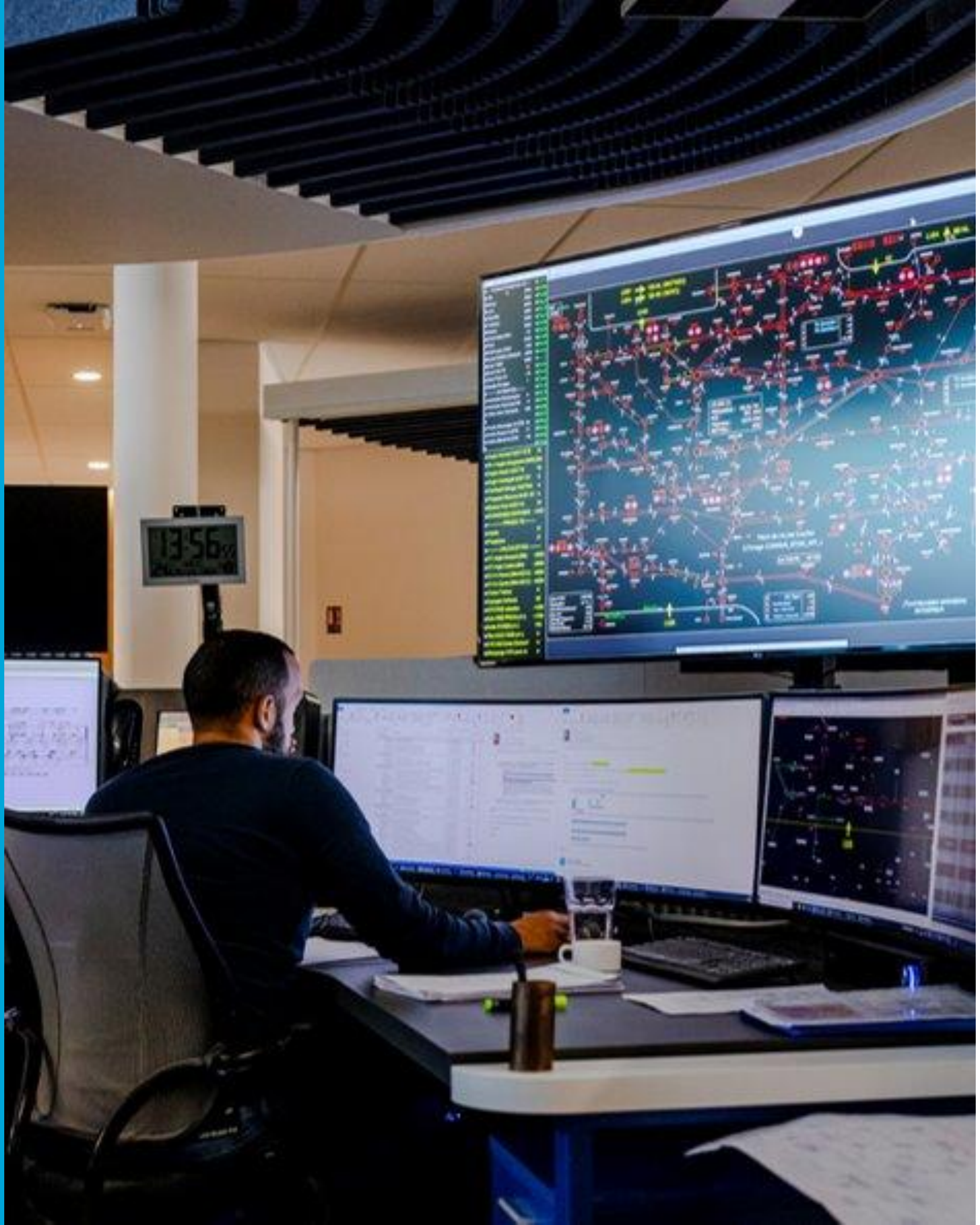
AGENDA



1 – The new rhythms of power system

a) Renewable energy sources are not only variable : they change the general pattern of residual load and electricty prices

b) Flexibility increase is needed. But flexibility does not mean real-time : most volumes have to be scheduled in advance

c) High volumes of load shifting are achievable, but economic signals and technical activation coordination are needed

2 – The grid itself is in transition

3 – Optimal decision scheduling

a) The principles of the “last time to decide” logic

b) In practice, what can be forecasted ?

4- AI and the power system management

Why this agenda ?

Before coming to AI and mobilization of thousands and millions of actors, I intend in the presentation to explain to you the way power system is operated, and especially the time scames of decisions.

So that you fully understand that flexibilities do not mean everything in real-time at the last moment.

My moto is rather :

anticipate everything which can be forecasted

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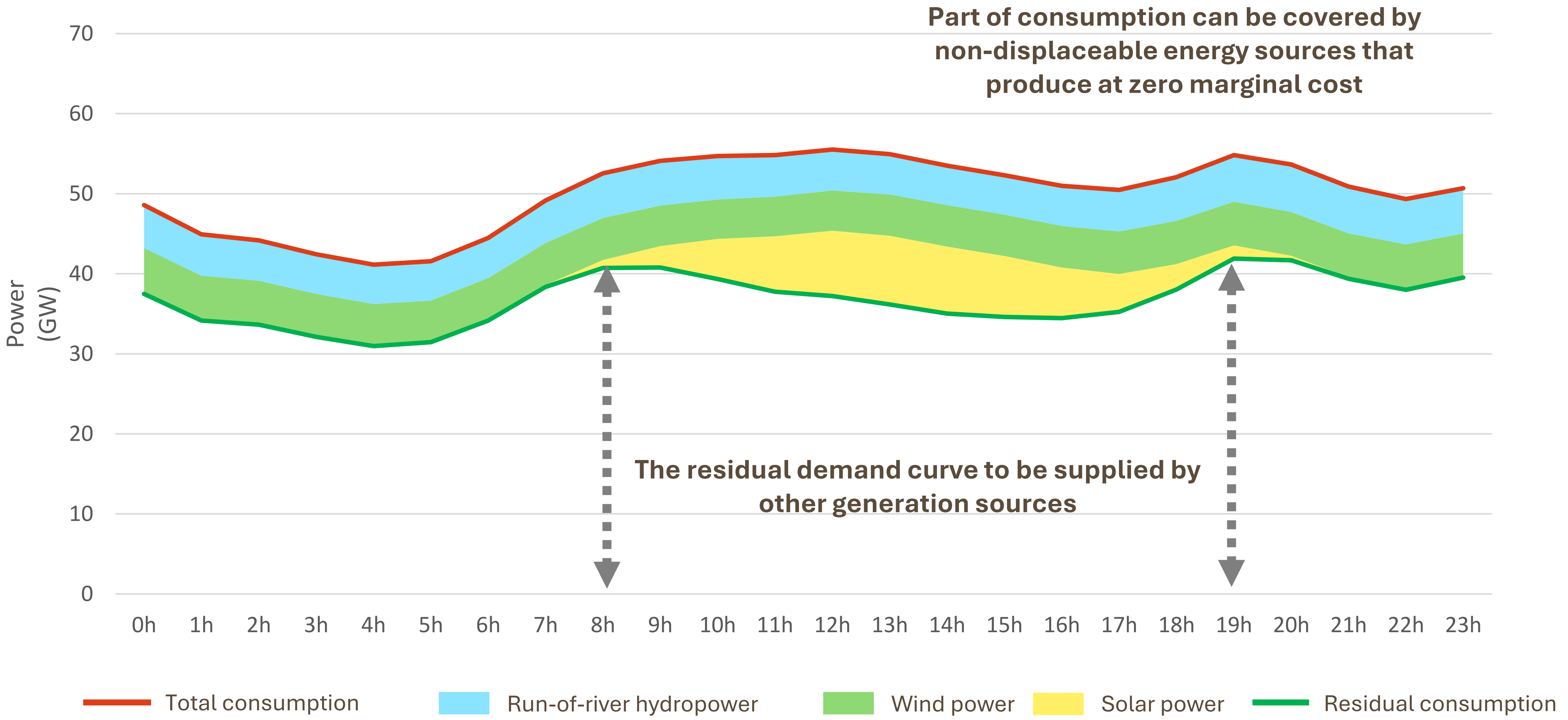
1 The new rhythm of power systems

The electrical system's flexibility needs are rising rapidly

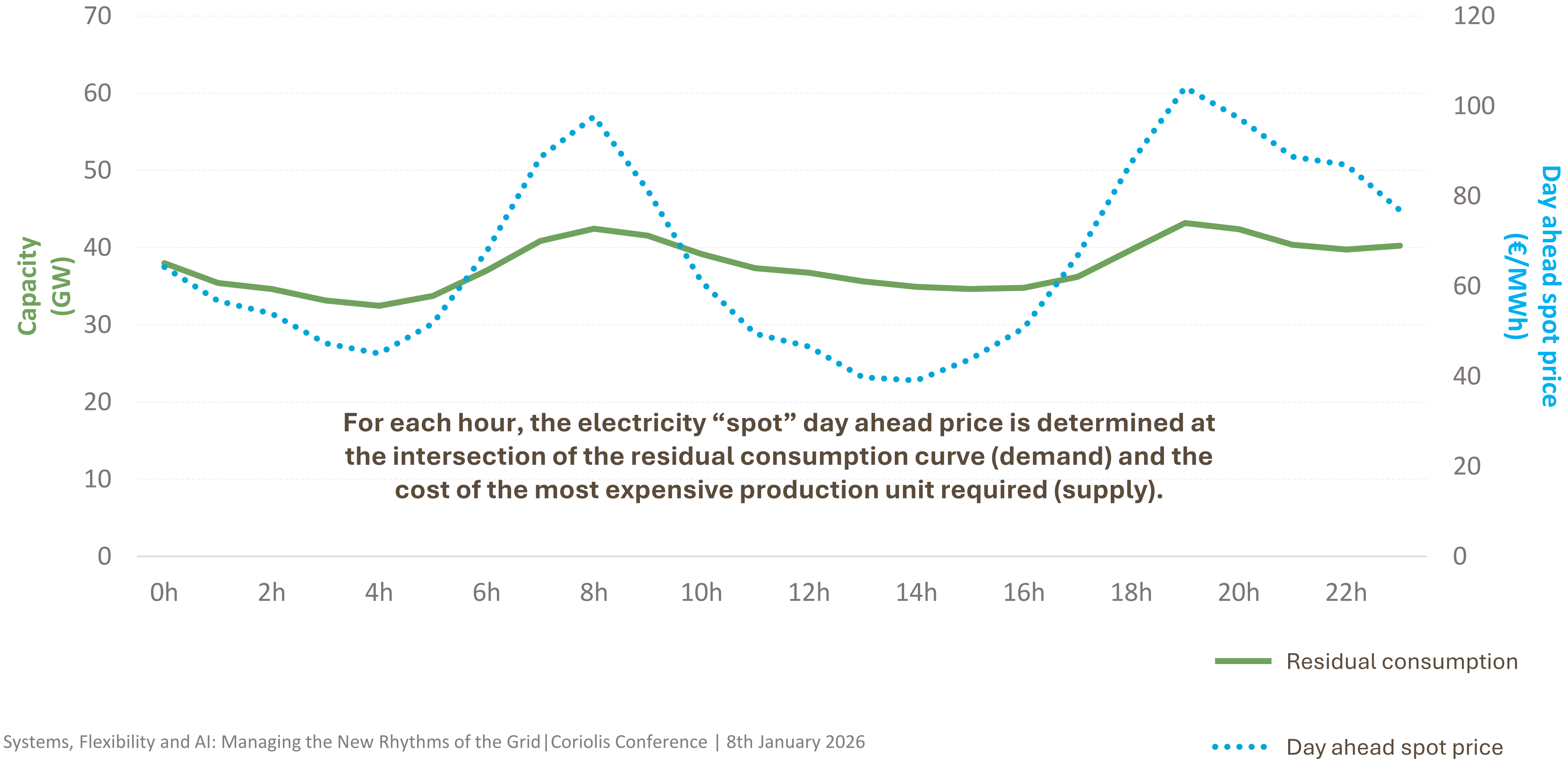
The right times of day to make regular use of electricity that is cheaper to produce: at night and midday

Average work days in France, in 2024



The best times of the day are reflected in the electricity spot price

Average work days in France, in 2025

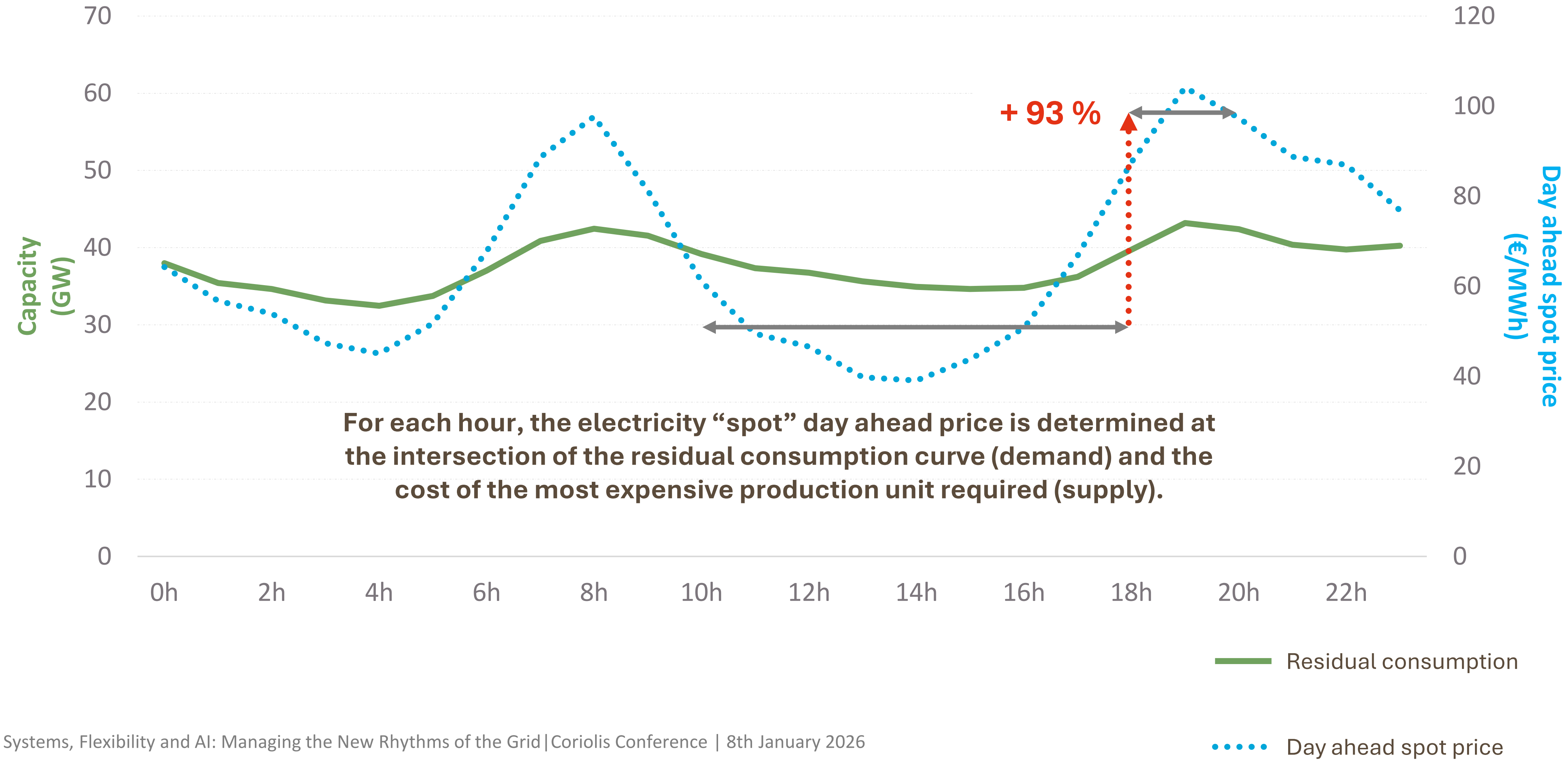


For each hour, the electricity "spot" day ahead price is determined at the intersection of the residual consumption curve (demand) and the cost of the most expensive production unit required (supply).

Opportunities for demand-side flexibility

The best times of the day are reflected in the electricity spot price

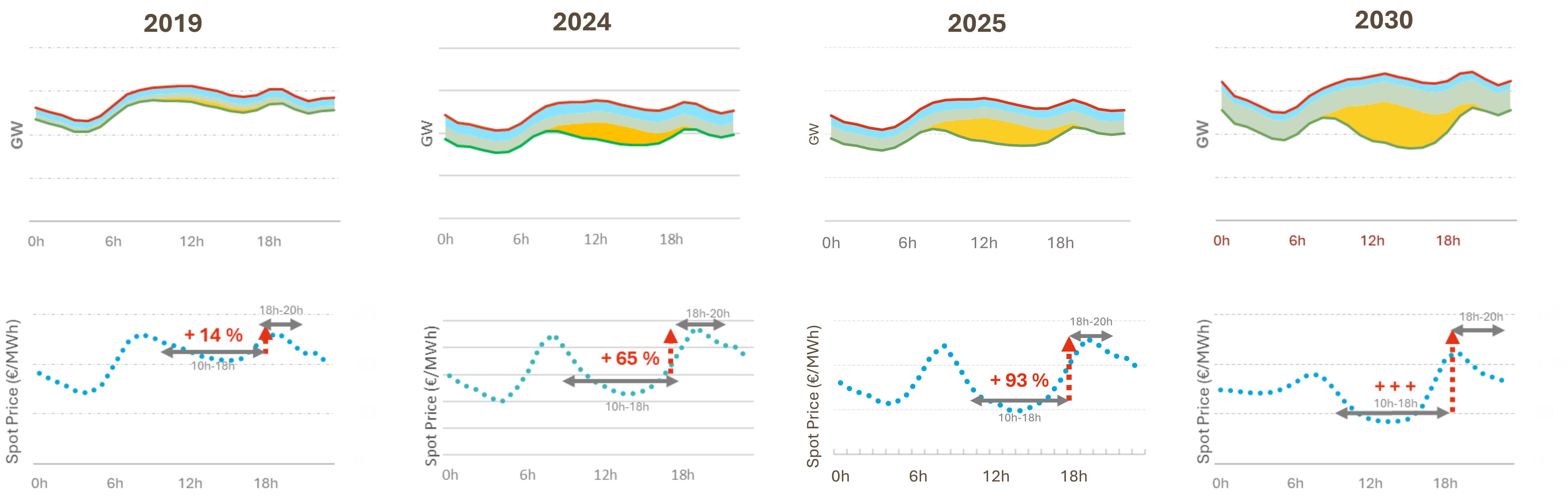
Average work days in France, in 2025



For each hour, the electricity "spot" day ahead price is determined at the intersection of the residual consumption curve (demand) and the cost of the most expensive production unit required (supply).

Spot market prices already show the rapidly increasing market opportunity for flexibility

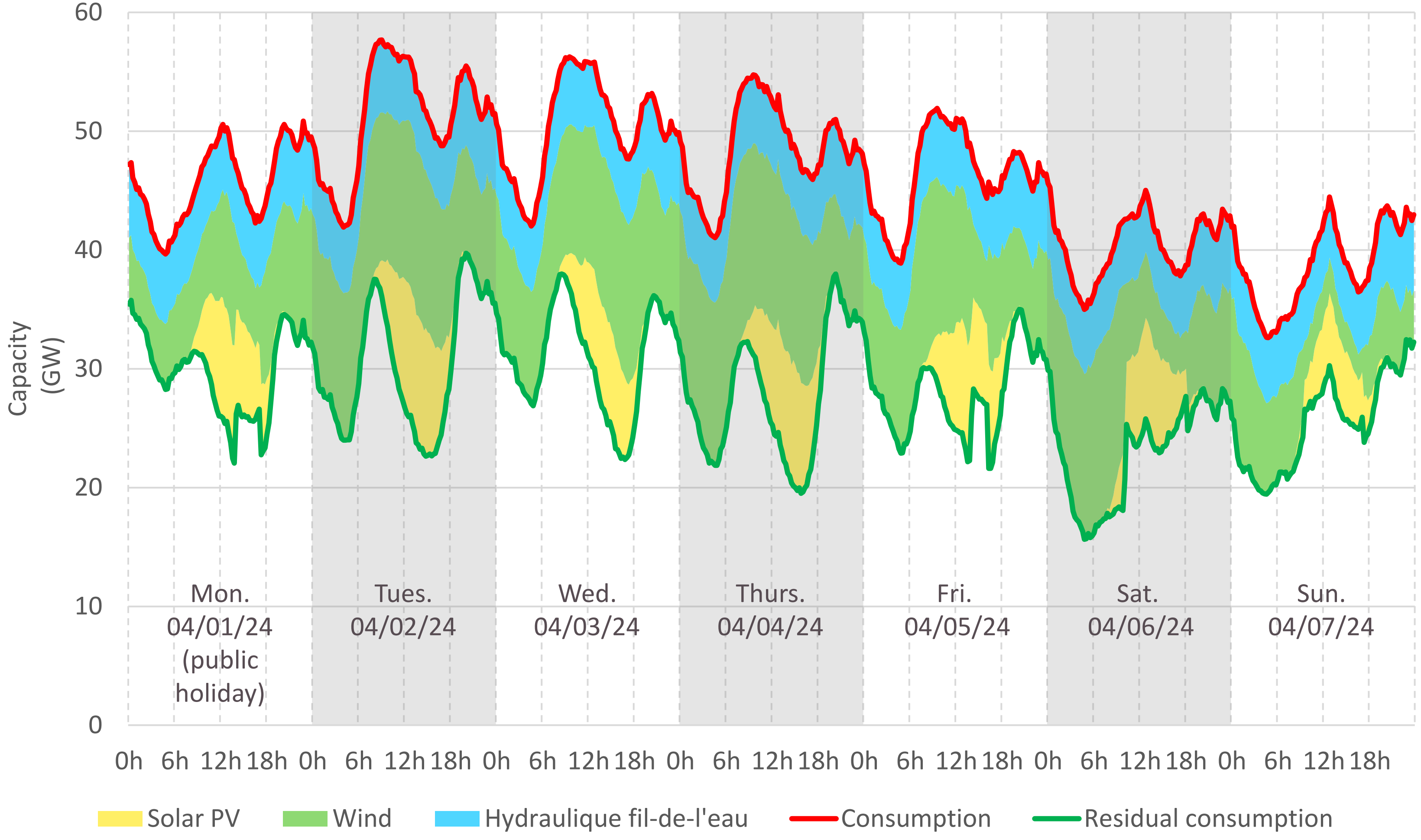
France, Average hourly spot prices for work days



This opportunity is increasing at a very fast pace!

At intraweek and intraday scales, dynamic variations in wind, solar, and consumption modify residual consumption

Example of residual consumption variations for the week of April 1, 2024



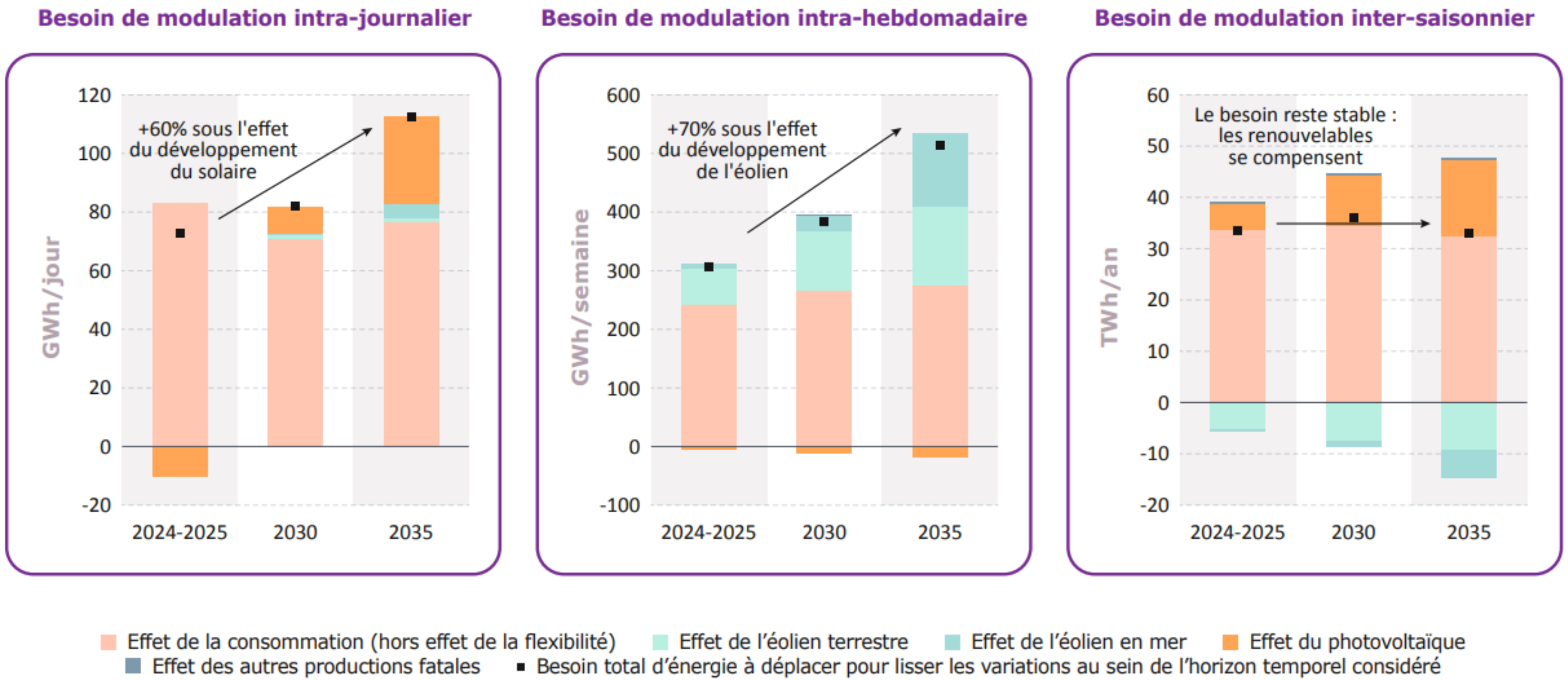
To the regular and structural patterns of "average" residual consumption are added less predictable, more dynamic variations, related to

- Solar PV variability
- Temperature-sensitive consumption variability
- Wind variability

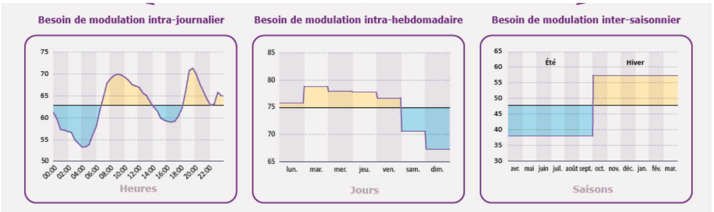
Intraday and intraweek flexibility needs are the ones that are increasing

[RTE, Bilan prévisionnel 2023 Chap. 6 : EOD et Flexibilités, juillet 2024]

Evolution of energy modulation needs at intraday, intraweek, and inter-seasonal scales (scénario A – reference, for the 2025, 2030, and 2035 horizons)



The graph above shows the variations in 'modulation needs,' estimated as the amount of energy to be shifted to smooth residual consumption, before any flexibility measures are applied.



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1.b

Flexibility increase is needed.
But flexibility does not mean real-time : most volumes have to be scheduled in advance

Four types of flexibility

Four different types of flexibility for supply and demand balance

1 – Structural and regular flexibilities
Positioning shutdowns of generation plants and structuring consumption when electricity is low-carbon and cheap

2 – Dynamic flexibilities
To meet occasional needs (cold spells or when wind generation is low)

3 – Balancing flexibilities
Compensate for contingencies within RTE's operational window (between 1 hour in advance and real time)

4 – Emergency flexibilities
Dealing with exceptional, post-market situations

Decreasing needs in volume

Y-3 à D-7	D-7 to H-1	H-1 to real time	
Futures market	**Day-ahead (SPOT) and intraday markets**	**Balancing mechanism and ancillary services**	éco watt / éco watt

The capacity mechanism brings additional revenue to ensure security of supply

Different types of solution

Demand response

Battery storage

Pumped hydro

NEW – Controllable generation units, including low-carbon thermal generation

TSO's balancing needs represent only a small part of the overall flexibility needs

RTE's balancing services represent a small share of the total need for flexibilities and will not be the ones that will increase the most in the future.

The Adjustment Mechanism no longer has the same role as in the past: it is only used to manage hazards in the RTE Operational Window (1 hour before real time)

Frequency System Services

FCR

Primary reserve

By the end of 2023, almost all of them should be equipped with stationary batteries, which are very suitable for this service.
The need will evolve if the dimensioning incident evolves at European level

0,5 GW → **0,6 GW**

aFRR

Secondary reserve

Provided by means capable of holding 2 hours of energy, it will increase due to greater variability in production and the reduction of the operational window.

0,7 GW → **About 1 GW**

Current orders of magnitude

Orders of magnitude projected in 2030

Mechanism Adjustment (MA)

mFRR and RR

Tertiary reserve

It will increase due to greater variability in production and the reduction of RTE's operational window.

1 GW and **0,5 GW** → **1,3 GW** and **0,7 GW**

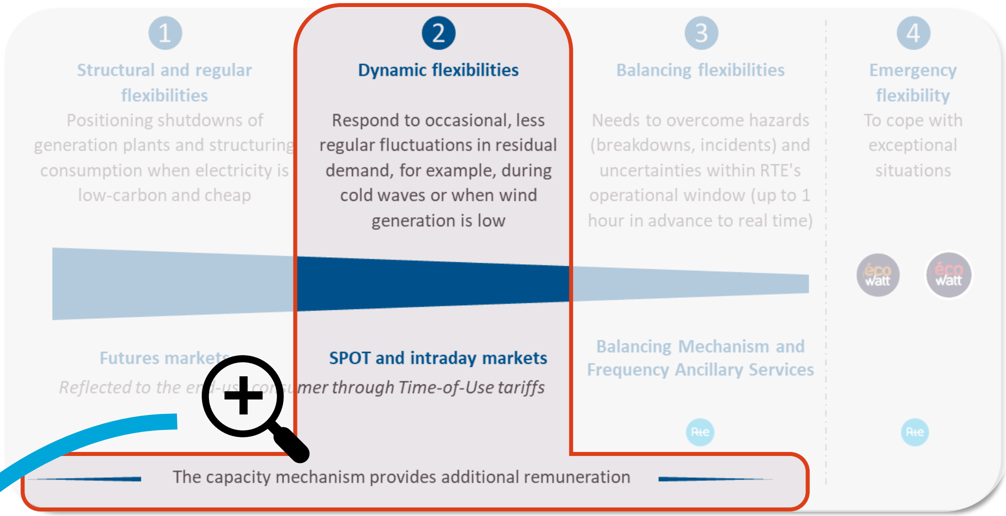
Total need

On the MA, only a minimum base of reserves is contractualized. The rest of RTE's need is covered by the obligation to offer the increased availability for the means of generation connected to the TOR.

This total requirement is now for upwards need between 1.5 and 3 GW and for downwards ones between 0.5 and 4 GW.

Power system flexibility needs, for now and for the future

There are two types of dynamic flexibility services designed to smooth fluctuations of residual demand that are predictable between a few days to an hour before real time and to optimise further than regular flexibility



Two use cases to meet the dynamic needs of the power system, which vary according to the notice period and the economic optimisation mode

Optimisation

1. Intra-weekly optimisation

Optimisation of the placement of planned consumption on a weekly basis: industrial maintenance, EV charging, etc. in relation to variations in wind and temperature that can be predicted a few days in advance.

2. Daily and intra daily optimisation

Optimisation of the scheduling of shiftable loads and consumption of adjustable loads throughtout the day, when is possible.

Insurantial

Load-shedding

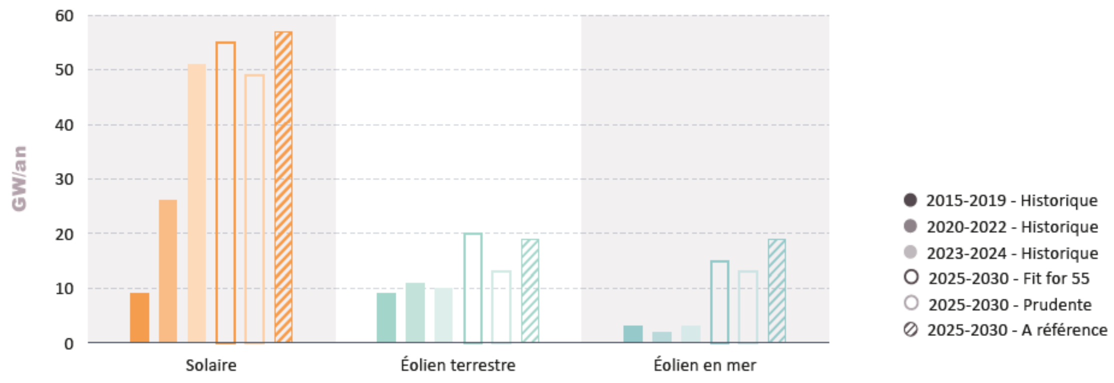
In case of moderate physical risk for the power system, a « pre-EcoWatt » mode, which need is signalled by RTE and paid for by the capacity mechanism (MECAPA) in addition to energy market price: Stopping industrial production, home office, etc.

Solar photovoltaic is the energy source growing the fastest this decade

Three phases in the development of three energy sources:
By 2030 for solar photovoltaic, after 2030 for offshore wind, and from 2035 for nuclear

Historical (2017–2022) and projected development rates in the 2023 Reference Scenario of the Power System Outlook (*Bilan prévisionnel*), for France and its neighbors

Rythmes d'installation des nouvelles capacités renouvelables, historique et projections dans les trajectoires européennes du Bilan prévisionnel 2025



By mid-2029, in France:

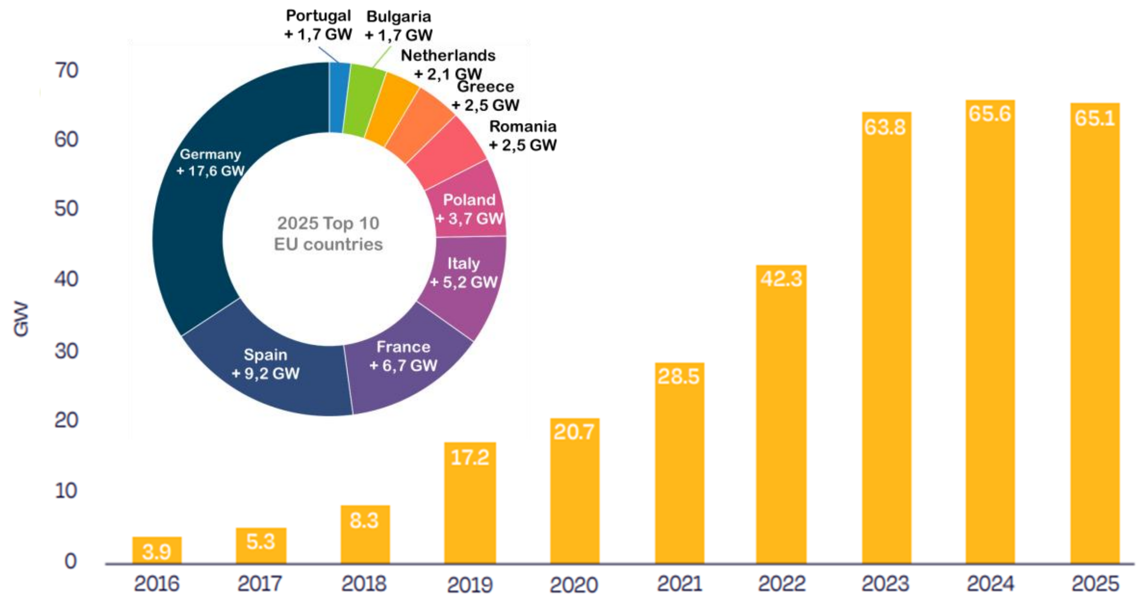
+ 8 à 10 GW

<u>+ 20 à 30 GW</u>

+ 3,5 GW

By 2025, more than 65 GW of solar PV has been installed in the European Union :
The power system is transforming at a rapid pace

EU annual solar PV installed capacity 2015-2025



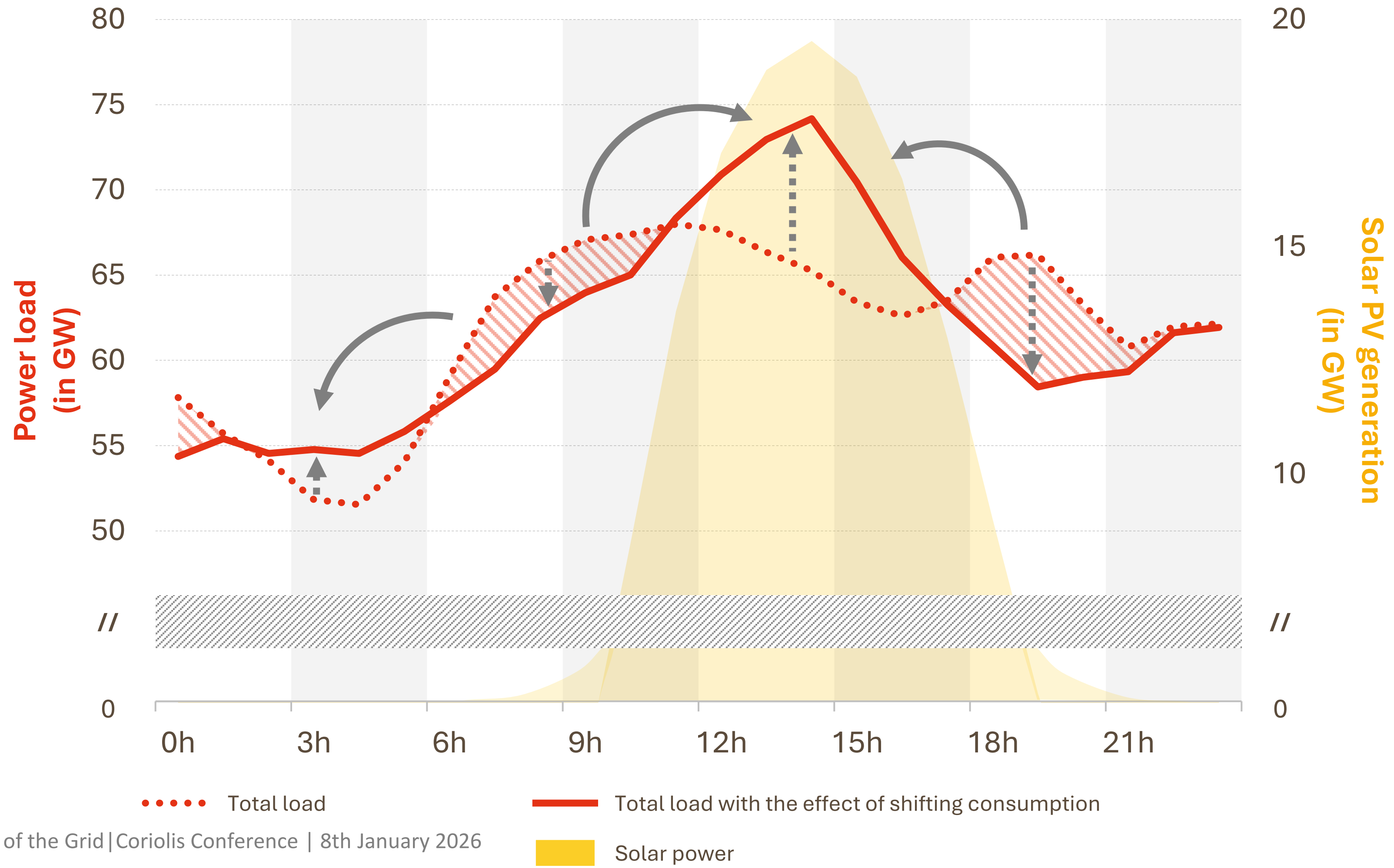
Flexibility means shifting part of consumption towards times when electricity is cheaper to produce: at night and during the day

Illustration of the effect of time shifting and modulation on electricity consumption

The aim is to bring together two worlds: energy management in buildings and energy procurement.

Shifting part of your consumption to the night and the middle of the day can be a source of savings ...

... but how can you shift some of your consumption easily and without any loss of comfort?



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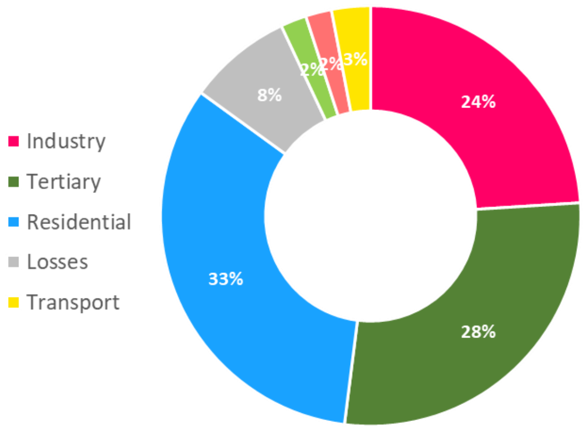
1.c High volumes of load shifting are achievable, but economic signals and technical activation coordination are needed

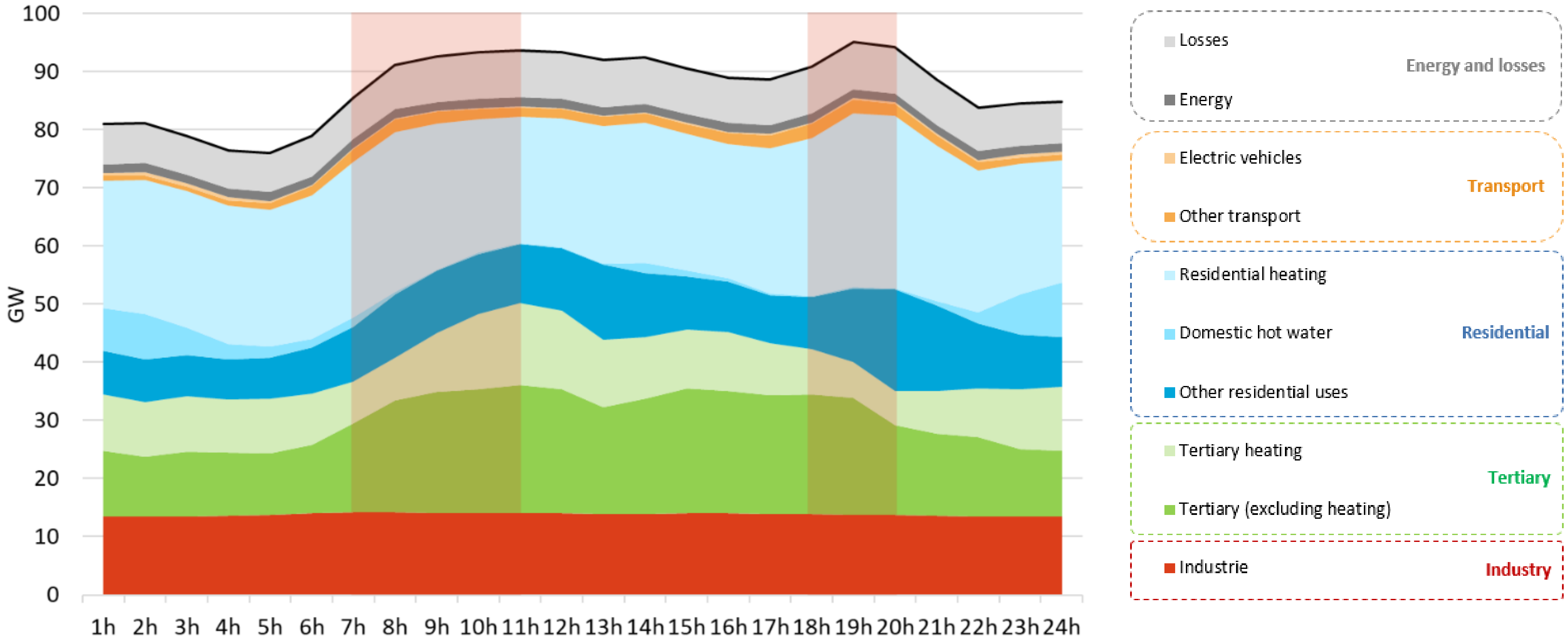
A proven and massive technical potential

In France, electricity consumption is largely structured by consumption in residential and tertiary buildings



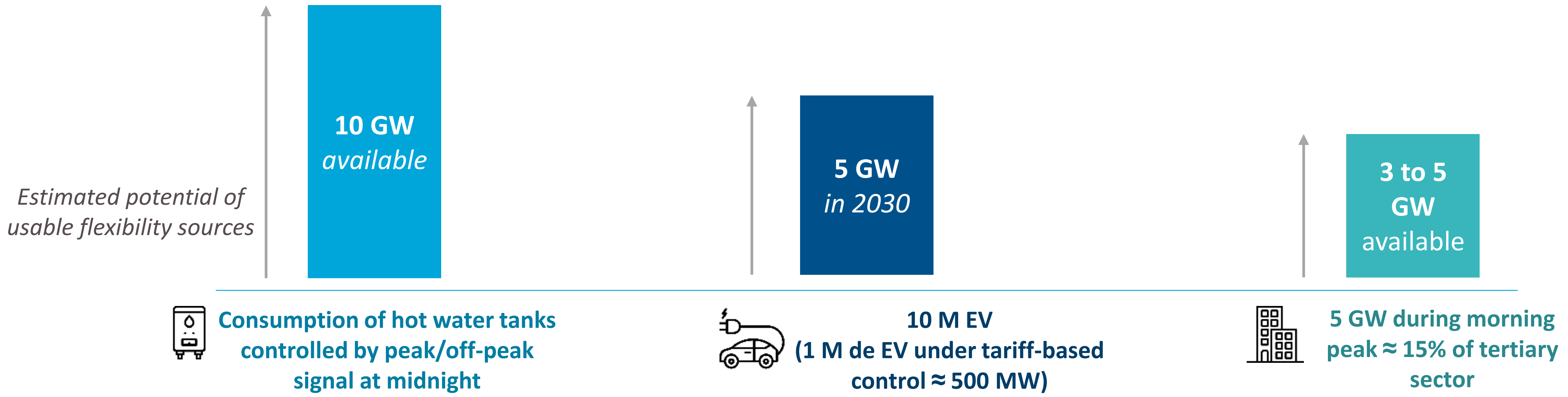
Distribution of electricity consumption by sector in France

Daily load curve for a working day in February 2021, cold temperatures



Shiftable consumption potential already exists

Several gigawatts of consumption already exist and can be shifted and modulated, offering significant leverage to make better use of production.



This flexibible demand is already needed to better use renewable energy during the day.
For example in France in 2024, 5GW of renewable capacity where curtailed on averge during negative spot prices hours.

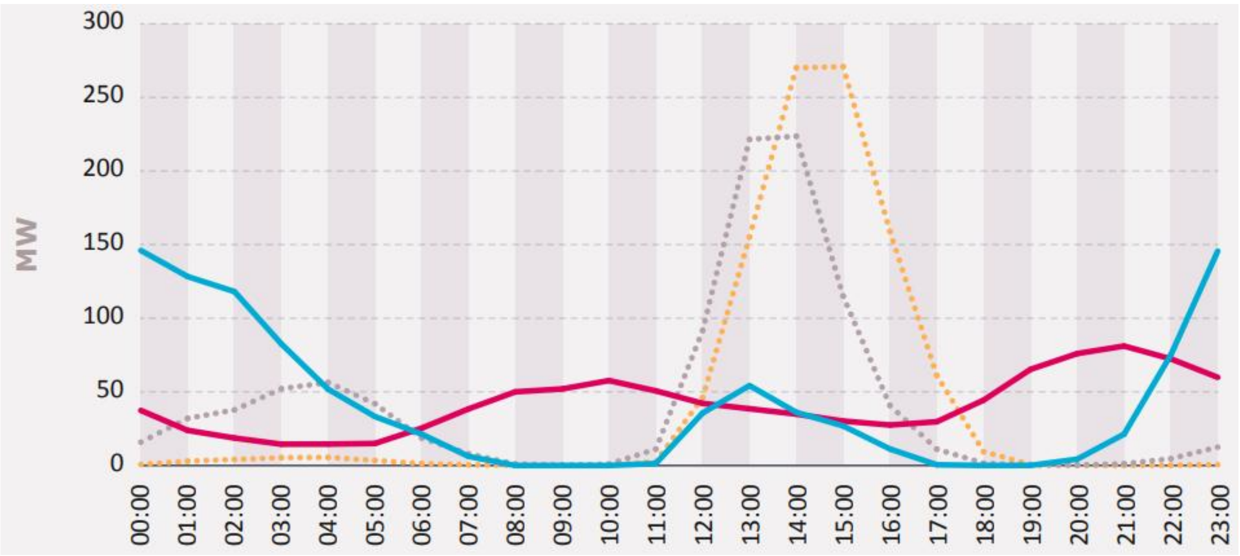
Price signals

Retails tariffs can play a crucial role to incite consumers to shift their load

In 2035, the tariff-based control of domestic hot water systems could evolve to better align with periods when the power system has the greatest available margins

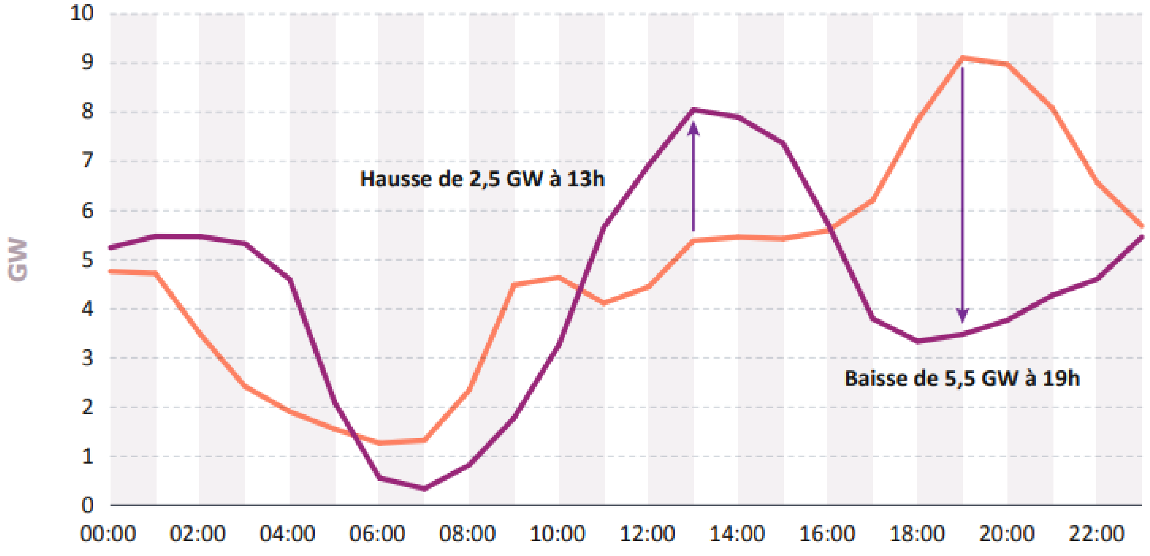
In 2035, the reference scenario forecasts a fleet of 18 million electric vehicles. Through tariff-based control, charging-related power demand could be reduced by 5.5 GW during 7 p.m. peak.

Consumption profile for domestic hot water according to control mode



Cotrolled consumption
Uncotrolled consumption
Controlled consumption (summer 2035)
Controlled consumption (winter 2035)

Charging profile for electric vehicles fleet, in an average working day according to control mode



Cotrolled consumption
Uncotrolled consumption

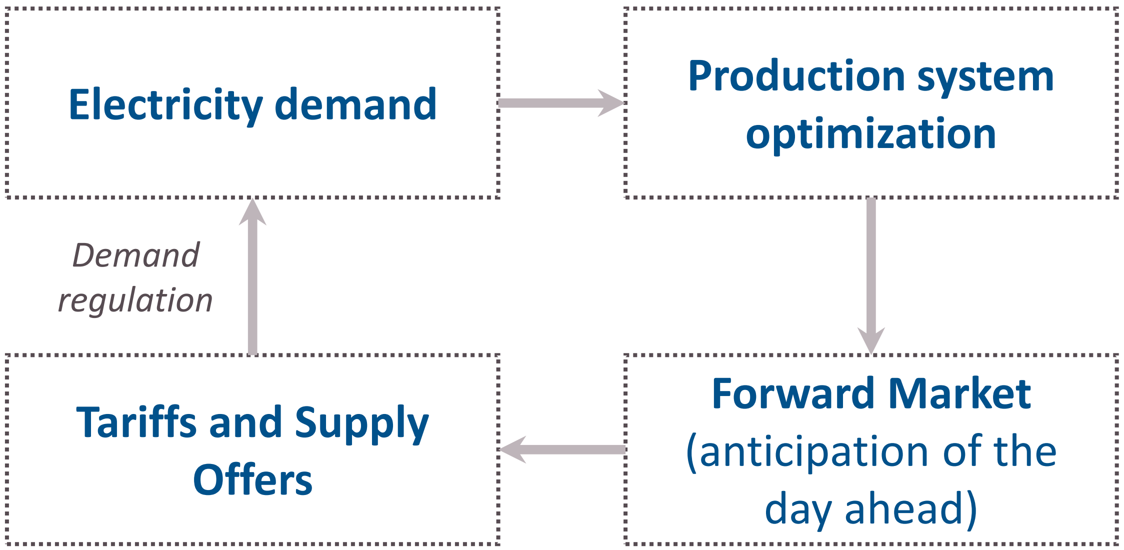
To design supply offers that respond to these flexibility needs, obstacles upstream and downstream must be addressed

Two types of barriers appear to exist: those related to supplier's procurement conditions and those concerning the incentives given to consumers to utilize their flexibility

Consumers want simple, fixed tariffs…

… without realizing that this deprives them of a way to reduce their bills

Do not confuse fixed prices in the sense of predictable prices with a single price for the entire year.



Suppliers' procurement

(notably via forward markets for peak/off-peak periods and the ARENH mechanism)

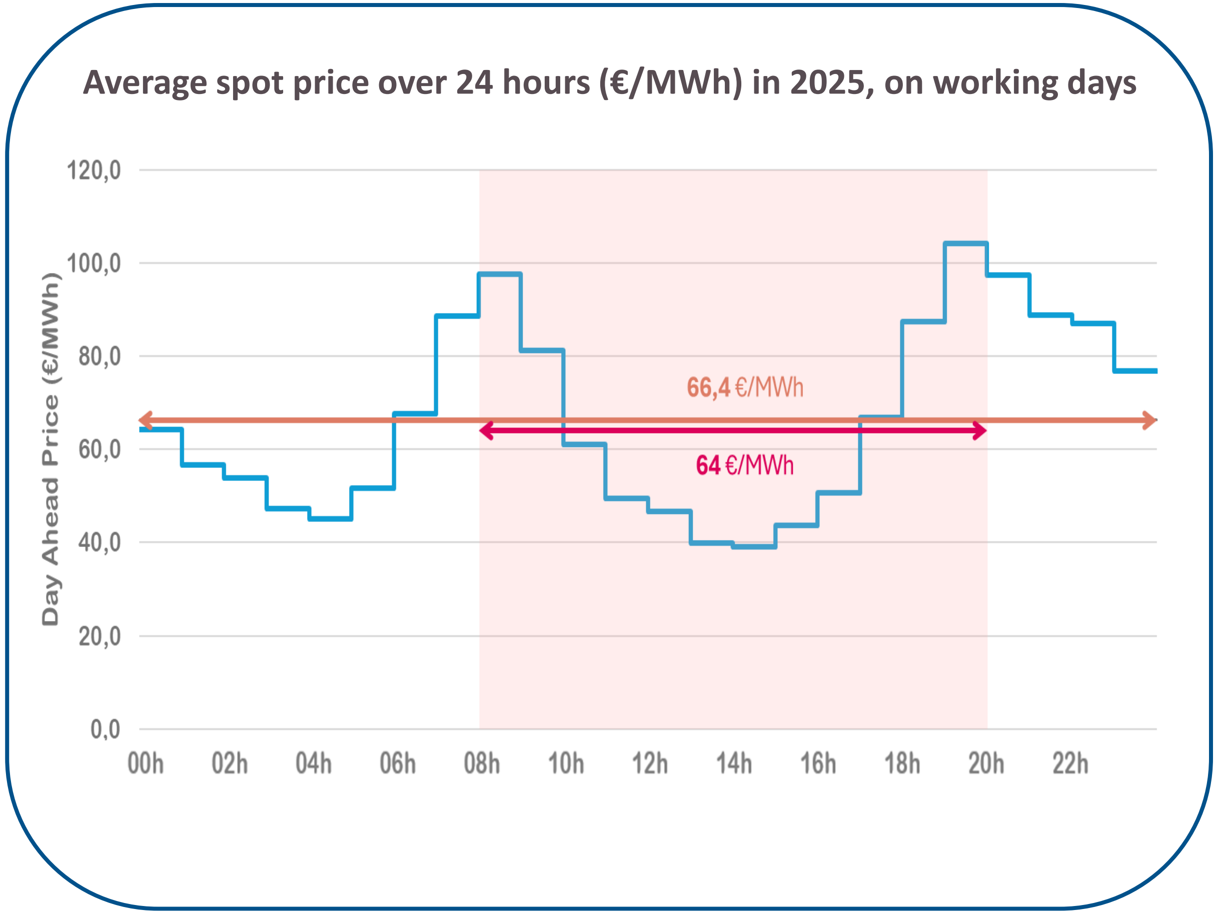
does not reflect the difference in production costs between peak hours and off-peak hours, when low-carbon electricity is abundant.

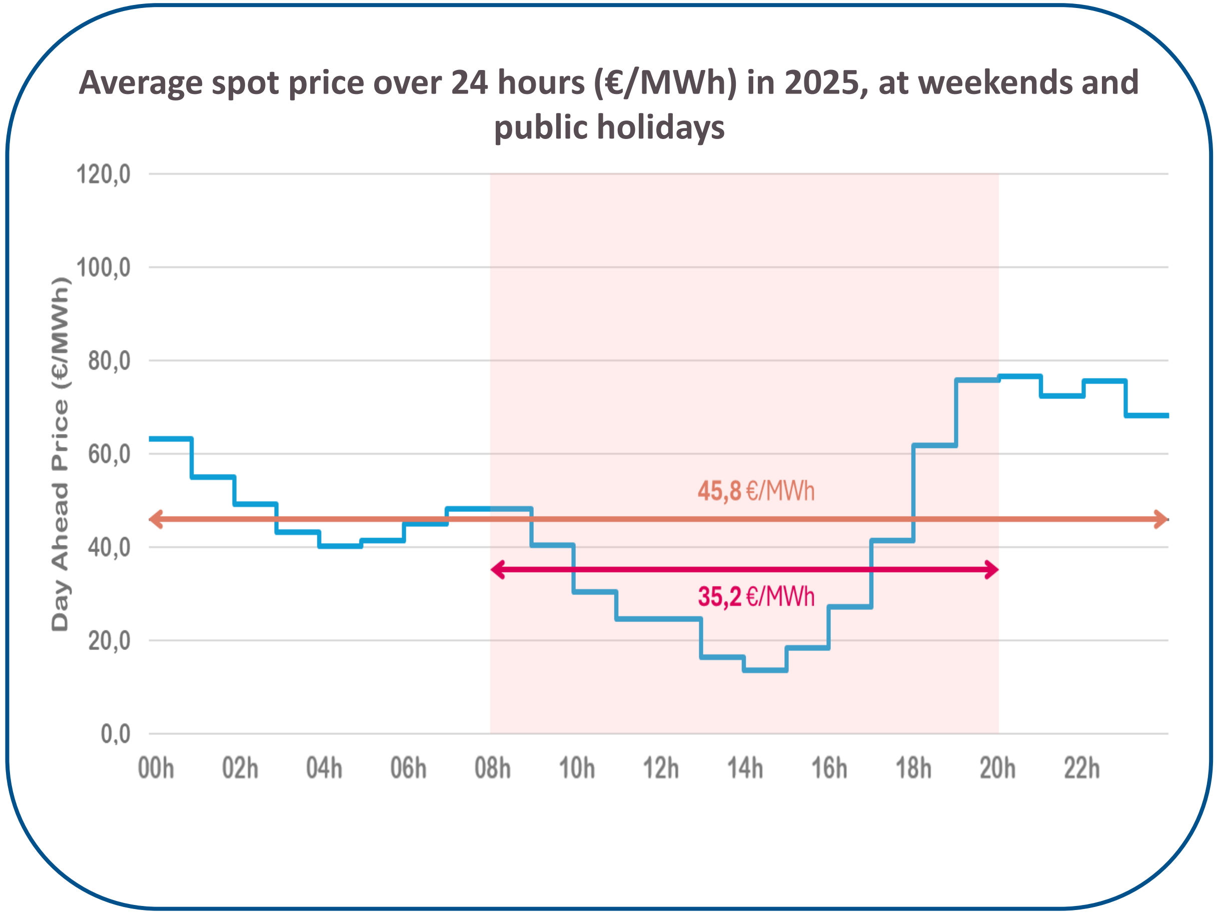
Focus on the tertiary sector :

- *Majority of tariffs are single-price (estimated: two-thirds of subscribed offers).*
- *Those who sign the contracts are not the ones managing the buildings: there is no link between changes in building management and bill reduction.*
- *Less incentive to monitor subscribed capacity than in the past*

Price signals

Futures market peakload products are no longer suited to the system's needs





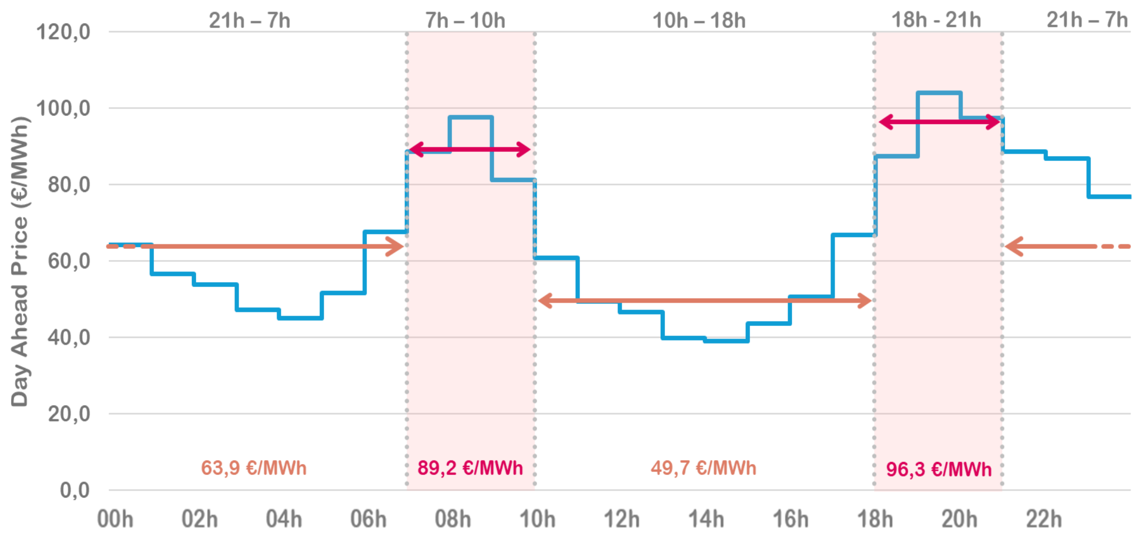
Average daily spot price « baseload » (24h) = **66,4 €/MWh**
Average daily spot price « peakload » (8h à 20h) = **64 €/MWh**

Average daily spot price « baseload » (24h) = **45,8 €/MWh**
Average daily spot price « peakload » (8h à 20h) = **35,2 €/MWh**

Price signals

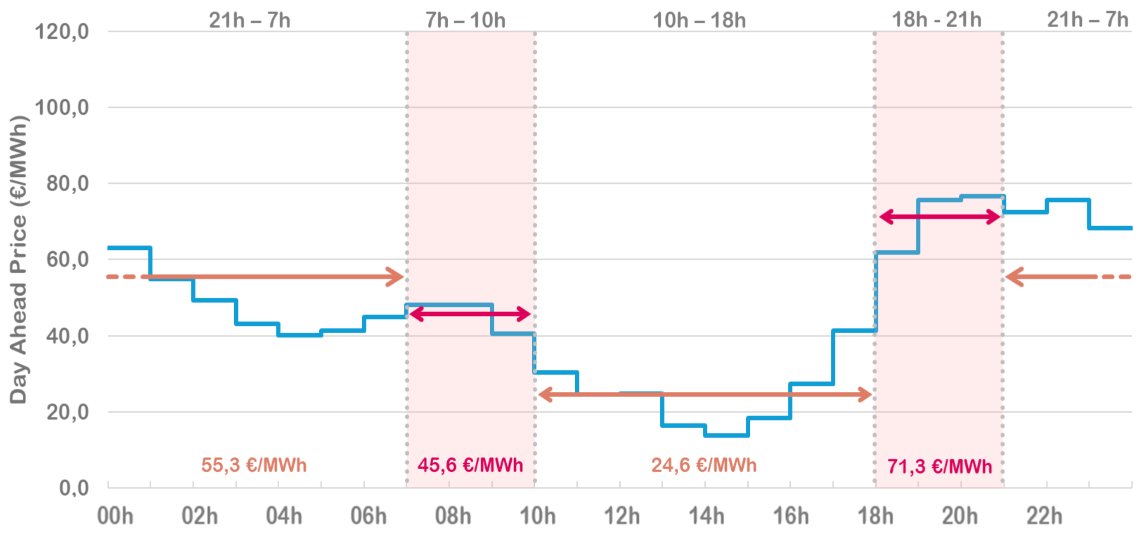
A shift toward four or five distinct time is desirable and would be more appropriate

Average spot price over 24 hours (€/MWh) in 2025, on working days



Average daily spot price « baseload » (24h) = **66,4 €/MWh**
Average daily spot price « peakload » (8h to 20h) = **64 €/MWh**

Average spot price over 24 hours (€/MWh) in 2025, at weekends and public holidays



Average daily spot price « baseload » (24h) = **45,8 €/MWh**
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To enable energy suppliers to build better retail tariffs,
the incentives they get from future market products should be adapted to the new power system rythms

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2 The grid itself is in transition : the physics of power systems is changing

Power system transformation in the upcoming decade implies a transformation or power system operation

2023 → 2035

An addition of different factors which alone constitue already a game changer

Renewable energy increase

PV BT: +25 GW (+280%)
Eolien terrestre: +17 GW (+77%)
Eolien Mer : + 16,5 GW (+1100%)

Consumption increase

+ 170 TWh (+ 38 %)

Storage development

1,2 GW de stockage en 2024

Constrained network development

Increase in european interconnexions

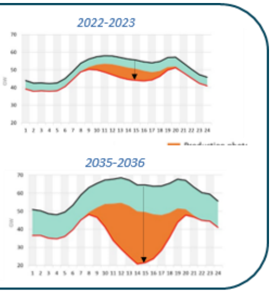
+ 13 GW (+ 31 %)

Power electronics devices everywhere

Reduction of thermal plants fleet and nuclear plants getting older

Nucléaire :+ 2 GW (+ 3 %)
GAZ : - 5 GW (- 35 %)
Hors Gaz : - 3 GW (- 75 %)

More variability

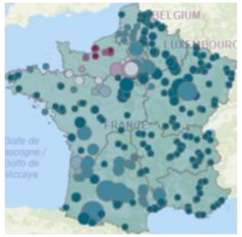


New opportunities for flexibilies development, and an increased stake on forecasting

Power flow variability increased, and more frequent congestions

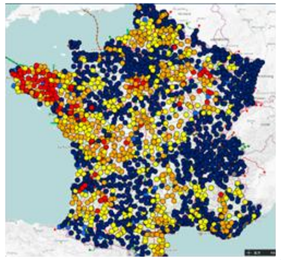
A need for more coordinated actions on wide areas

Lack of voltage control capabilities



Need to review the voltage control principles and ensure participation of all actors

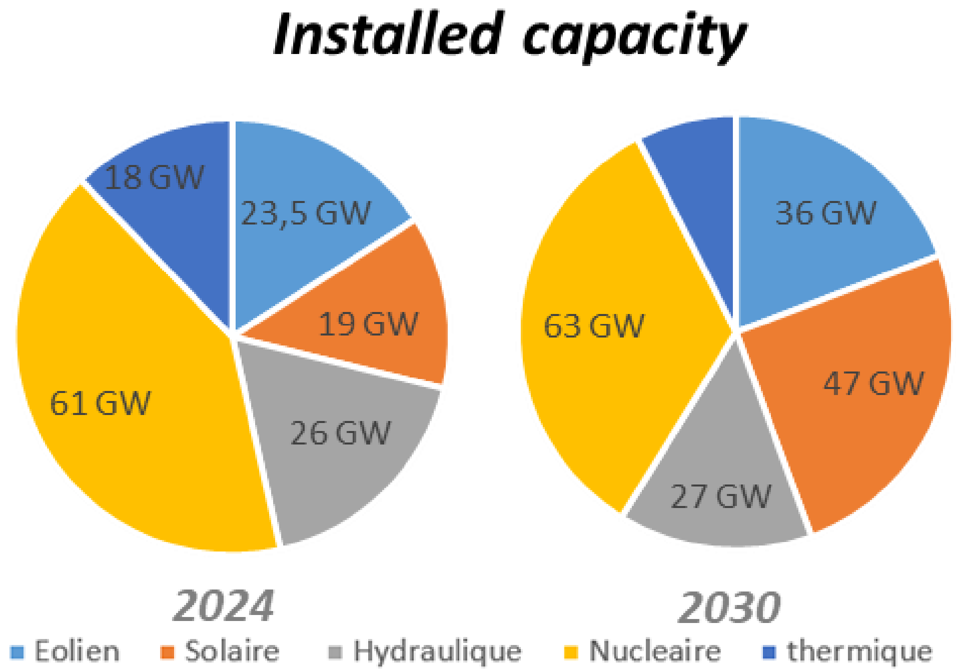
Instabilities caused by power electronics coordination

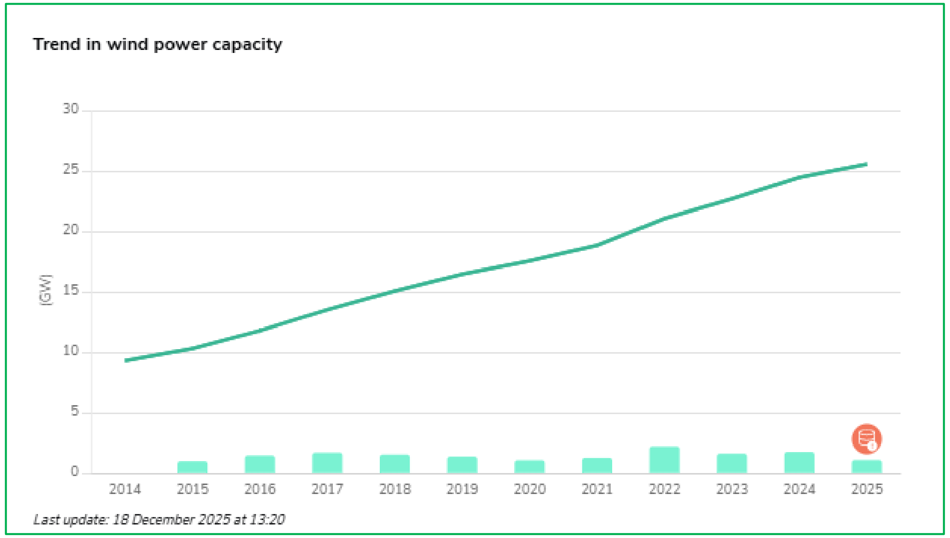


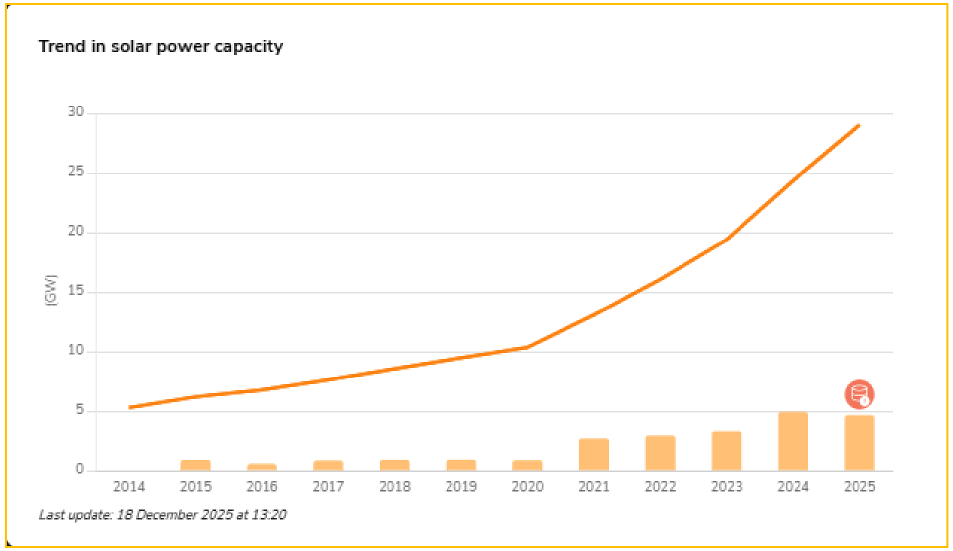
New phenomena to be studied and managed, with contributions of new actors

In this new framework, sunny spring afternoons become as tough to manage as winter evening peaks

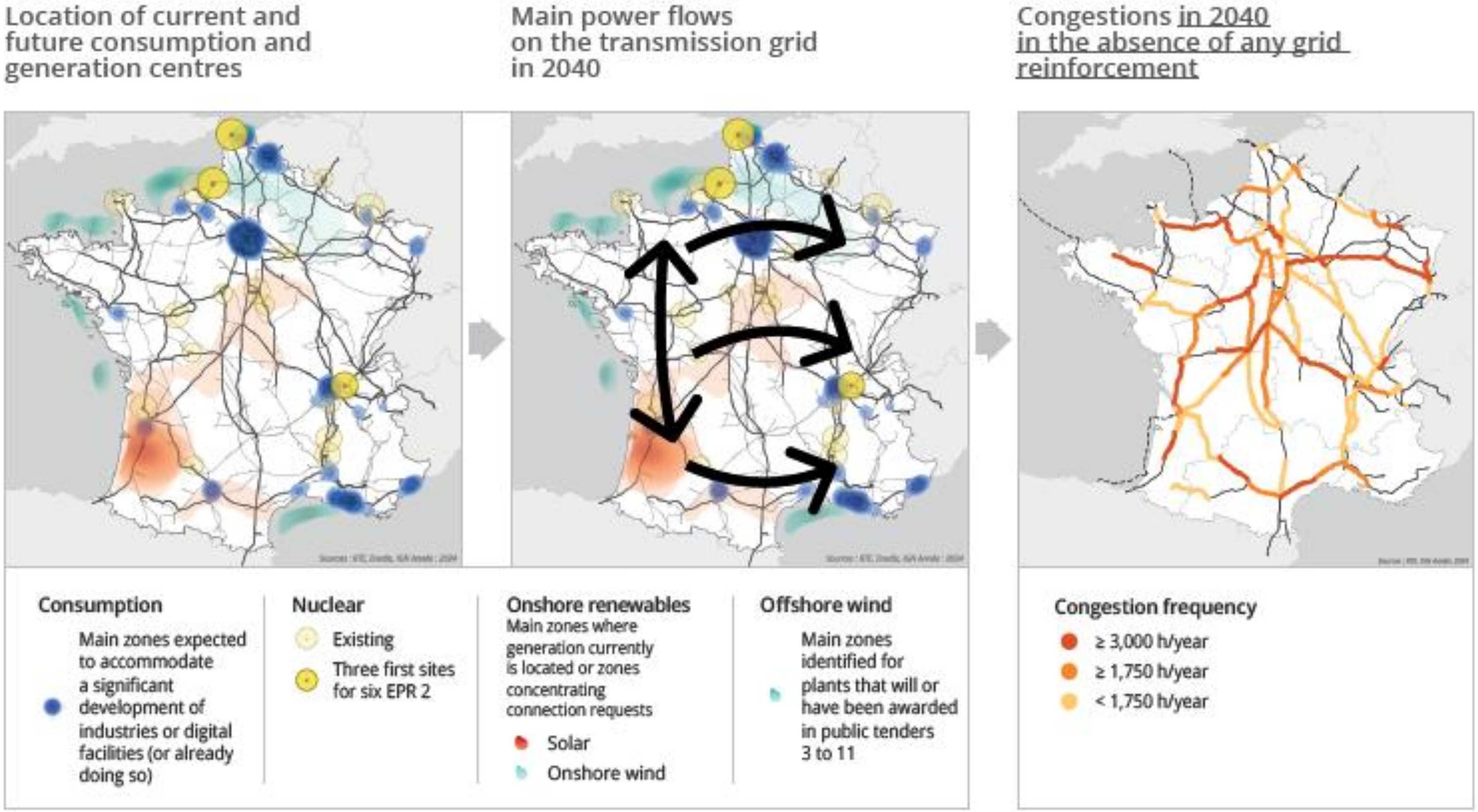
A fast evolution of the generation mix





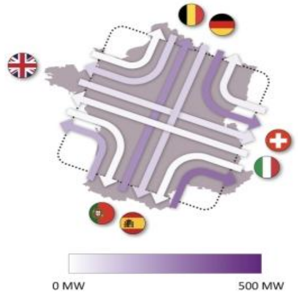


Geography matters : the energy mix and economy electrification trigger needs for grid reinforcements



Future generation assets as planned by the draft PPE 3 and resulting grid flows and congestions

- **Congestions** sur tous les niveaux de tension, **à la cible** et **en phase de travaux**
- Pour les congestions sur les réseaux HTB2 et HTB3, de **forts volumes de redispatching avec des variations en infra-journalier** (4-8 TWh/an) **et leurs impacts sur l'EOD**



Congestion management consists of activating other flexibilities, but on the same assets

Change the generation pattern :

- Lower generation in a zone
- Increase it in another
- With non incidence on the global balance

Can be achieved on any kind of asset :

- Bulk Generation (historic)
- Industrial consumption (recent)
- Storage (upcoming)
- Distributed generation (upcoming)
- Distributed consumption (upcoming

Needs new, local flexibility markets

Figure 1 – French public power transmission grid in 2025

3 Optimal decision scheduling

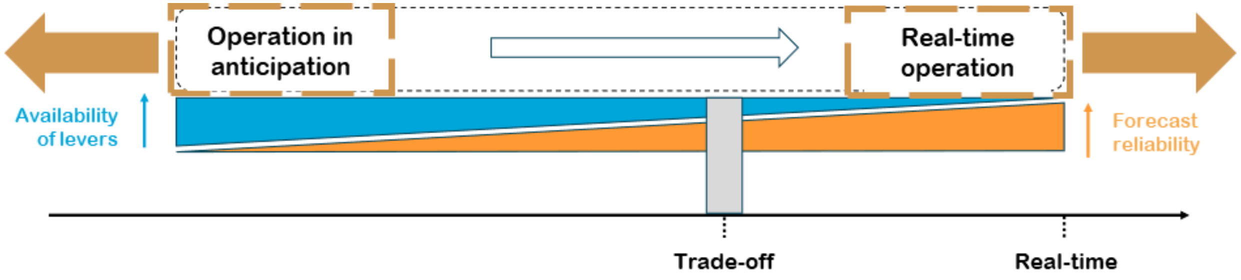
Anticipate everything that is predictable…

The dynamic management strategy of the power system is based on a balance between two approaches :

Preventive approach

Real-time optimized approach

Economic sub-optimization due to decision-making under high uncertainty, which may lead to mobilizing excessive volumes of flexibility to cover risks, while still having a lower unit cost



Technical risk of unavailability of resources

Economic additional cost : use of potentially more expensive resources because they can be mobilized more quickly

Safety risk in case of malfunction

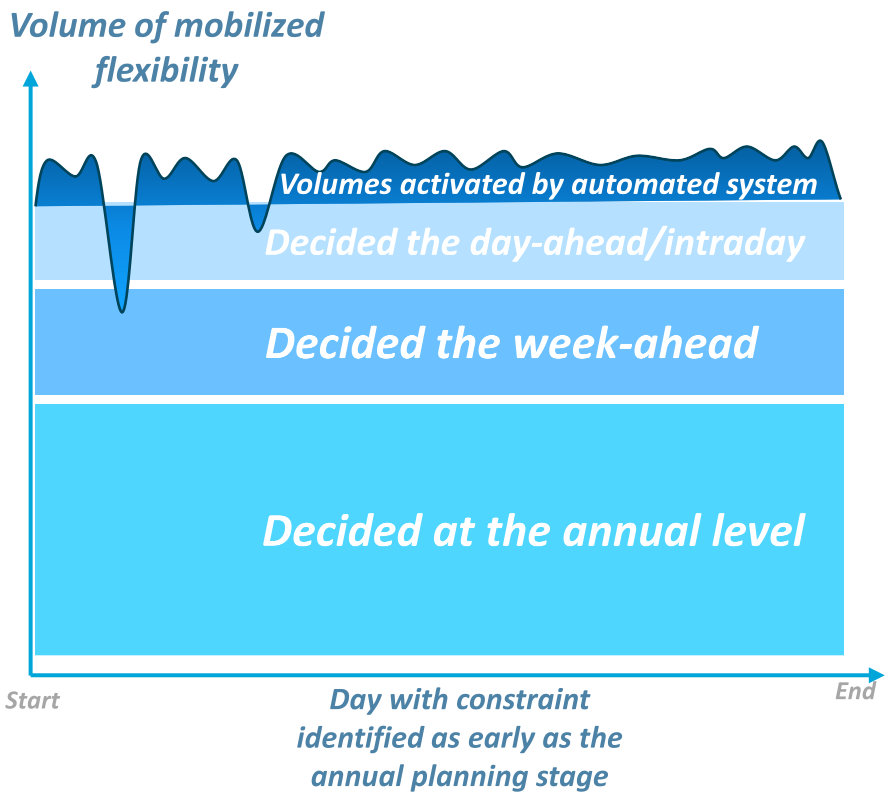
The principle of decision-making under uncertain future conditions does not change :

- Making decisions later helps limit uncertainties
- But it leads to losing certain flexibility levers, which are cheaper but require advance notice (last time to decide)

Anticipate everything that is predictable…

The proposed approach is of "*block + lace*" type

- Secure the largest volumes for what is predictable
- Then gradually adjust as uncertainties decrease, following a “**Last Time To Decide**” logic.
- Using more expensive resources, but for much smaller volumes.



Decisions result from the intersection between moments of information increase and the lead times required to mobilize levers (last time to decide)

Forecast data

- Residual consumption
  - Consumption
  - Photovoltaic generation
  - Wind generation
- European power flows
- Grid availability (infrastructure)

Levers

- Knowledge of flexibility levers, including their lead times and mobilization durations :
  - What can be activated on a weekly basis?
  - What can be activated on day-ahead?
  - What can be activated on intraday?
- Overview of the availability of flexibility levers across different time horizons

3.b What is exactly predictable ?

Fundamental question to optimize the dynamic management of the grid

The different time horizons of supply-demand balance in the electrical system

Dynamic flexibilities

Y-5 to M-1	*W-2 to D-2*	*D-1 to ID*	*H-30' to H+15'*
▪ No physical exchanges ▪ No weather information ▪ No renewable generation forecasts ▪ Forecasted view of the grid ▼ **Average prospective view of the regular and structural phenomena of the electrical system** *(Average level and shape of the load curve, characteristics of the generation mix, interconnections)*	▪ No physical exchanges ▪ Weather forecasts available ▪ Renewable generation forecast ▪ Grid availability ▼	▪ Physical exchanges ▪ Increasingly accurate weather and renewable generation forecasts ▪ Grid availability	**Balancing in « real-time» by RTE within the operational window** Represent a small proportion of total needs and will change little in the future

Increasingly precise dynamic forecast of the electrical system's state (W-2 to D-2 and D-1 to ID)

Different types of forecasts are necessary to anticipate operating conditions of the electrical system

Since the 1980s

Consumption (Temperature-sensitive):

- Determined notably from temperature forecast data provided by *Météo France*, up to 13 days in advance.

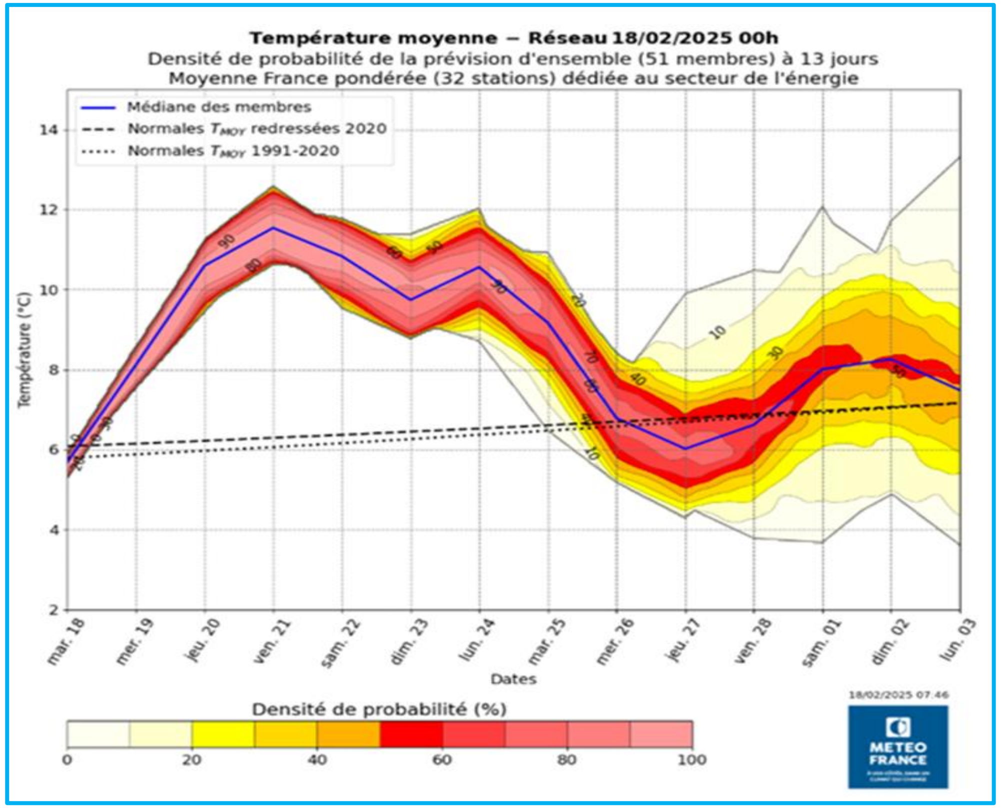
Since the 2010s

Renewables generation non-shiftable:

- In operational mode, solar PV and wind forecasts are available up to H+72 hours maximum.
- More forward-looking models allow forecasts up to D+13.

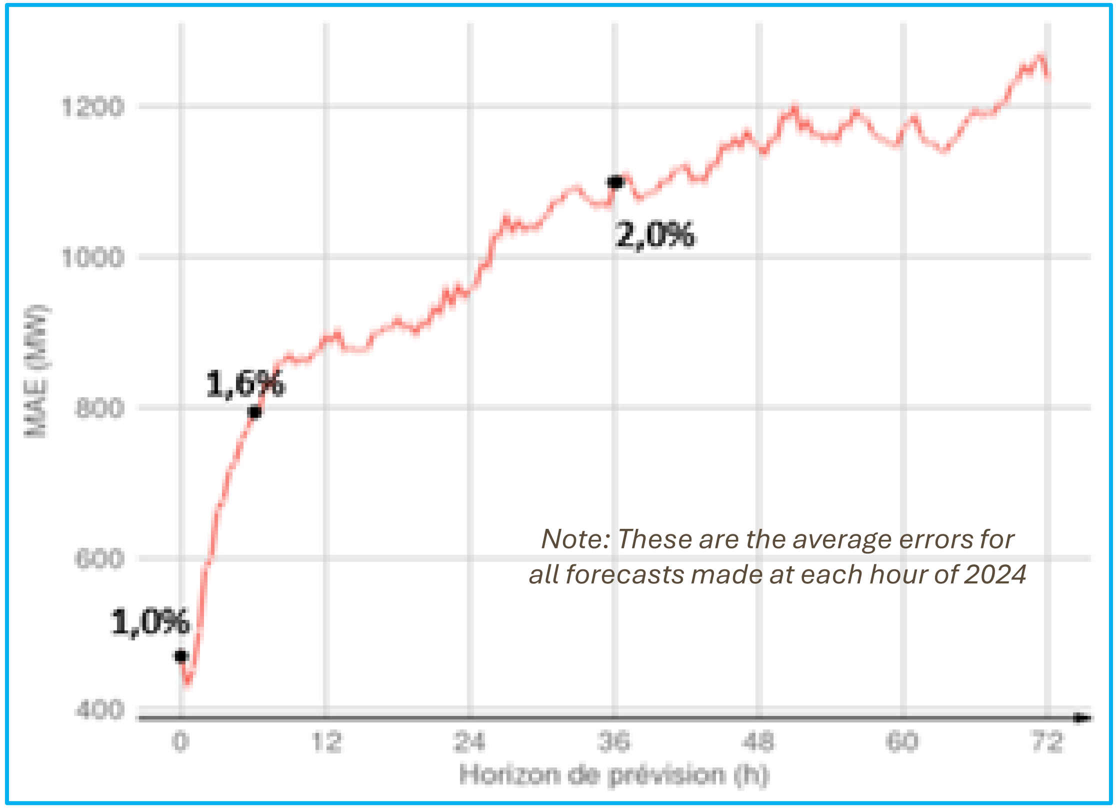
Consumption: determined notably from temperature data provided by *Météo France*, up to 13 days in advance

Temperature forecasts up to D+13 days (*Météo France* data)



The temperature forecast confidence interval widens rapidly from D to D+3, D+7, and then D+13

Average consumption forecast error at different time horizons in 2024 at the national level



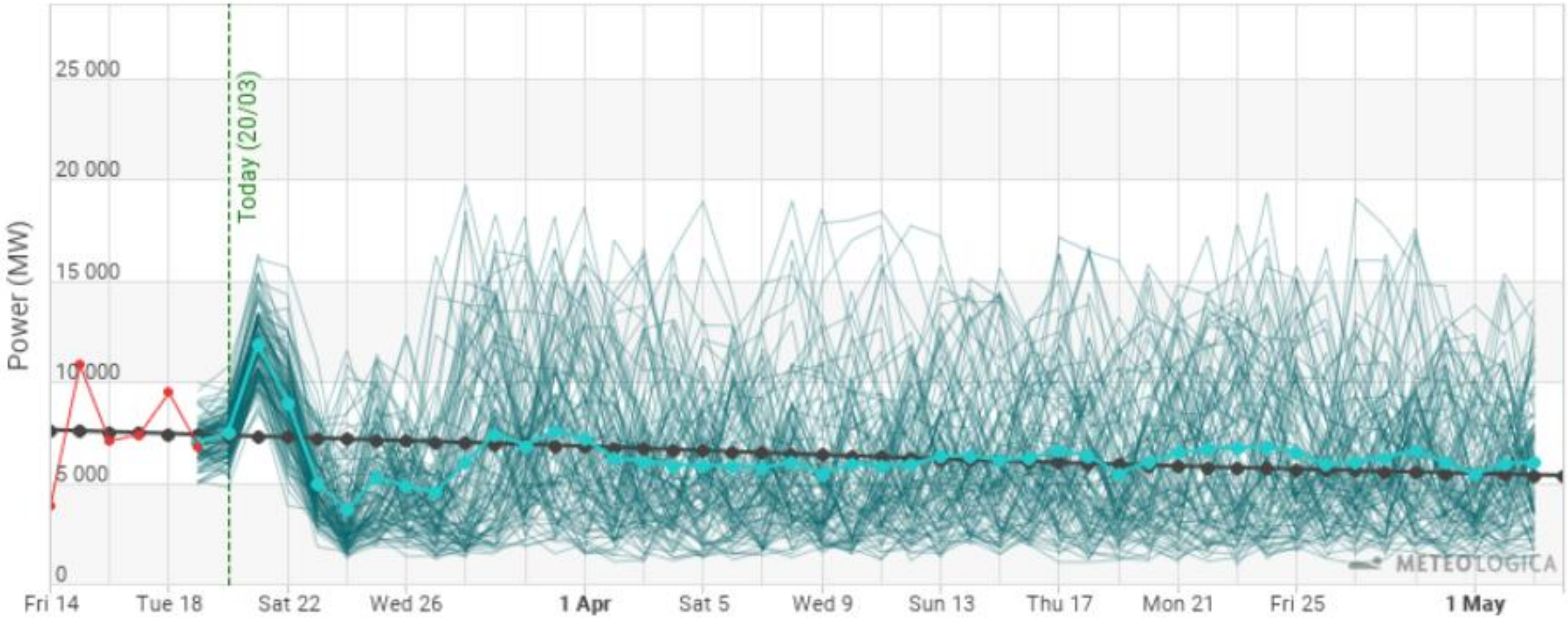
Note: These are the average errors for all forecasts made at each hour of 2024

Consumption forecasts become significantly more accurate 6 hours ahead of real time

Different types of forecasts

Overall wind levels can be forecasted up to one week in advance

Wind power forecasts up to 45 days in France

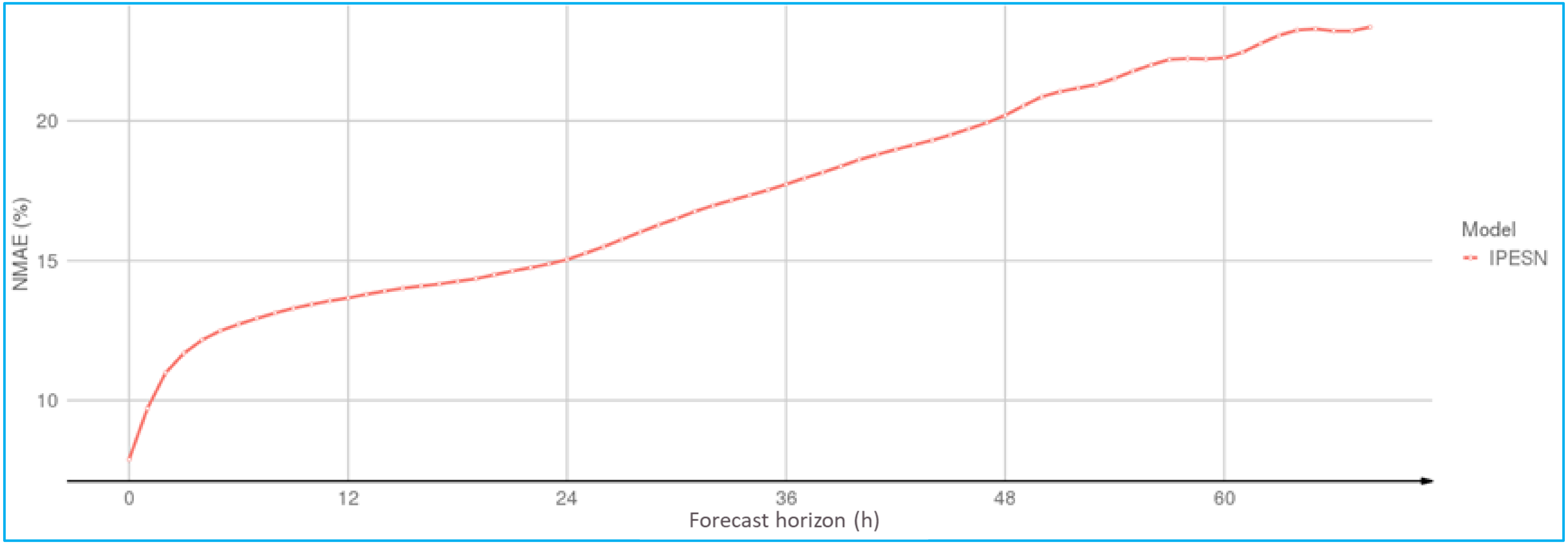


Wind Power average forecast ECMWF ENSEXT France
Wind Power observation France
Wind Power scenarios forecast ECMWF ENSEXT France
Wind Power seasonal average France

Different types of forecasts

Wind: up to 3 days in advance, with significant error beyond 3 to 6 hours ahead, which decreases rapidly as real time approaches

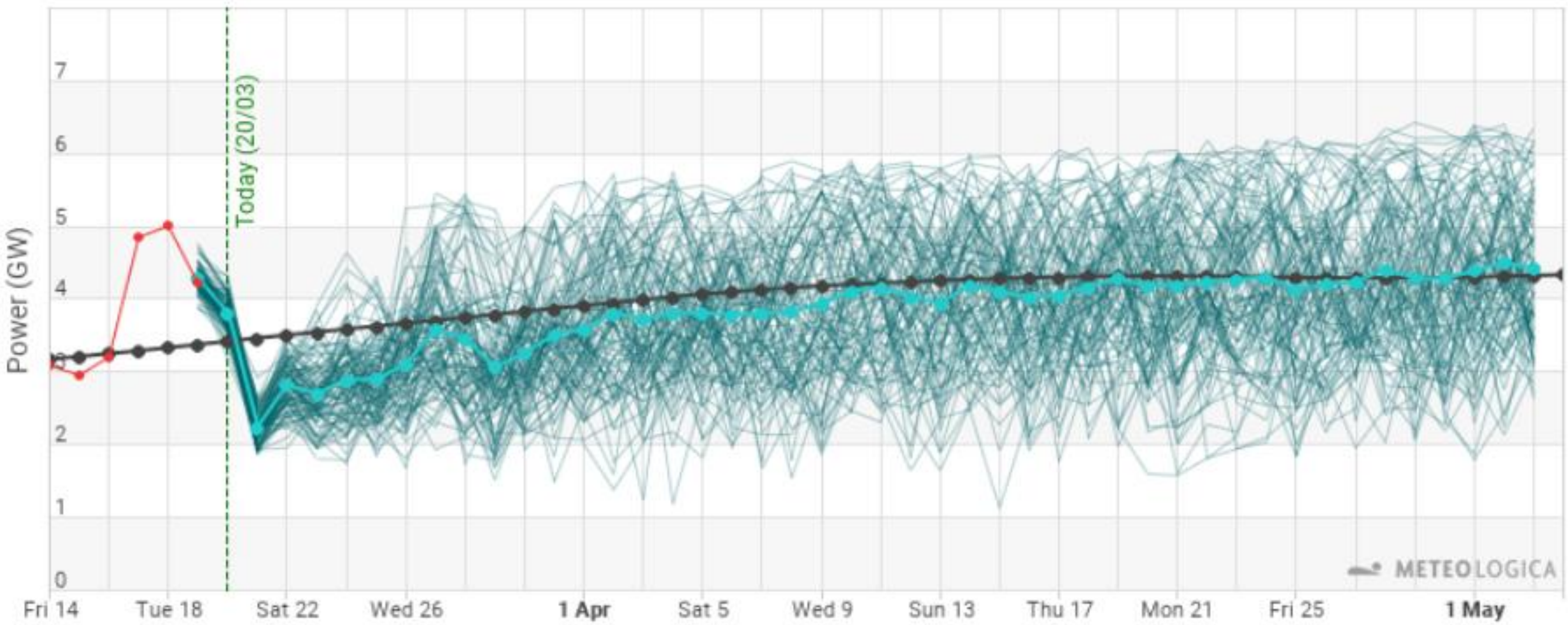
Average relative error of wind forecasts in 2024 according to the forecast horizon



Different types of forecasts

Overall PV production levels can be forecasted slightly less than one week in advance

Solar PV power forecasts up to 45 days in France

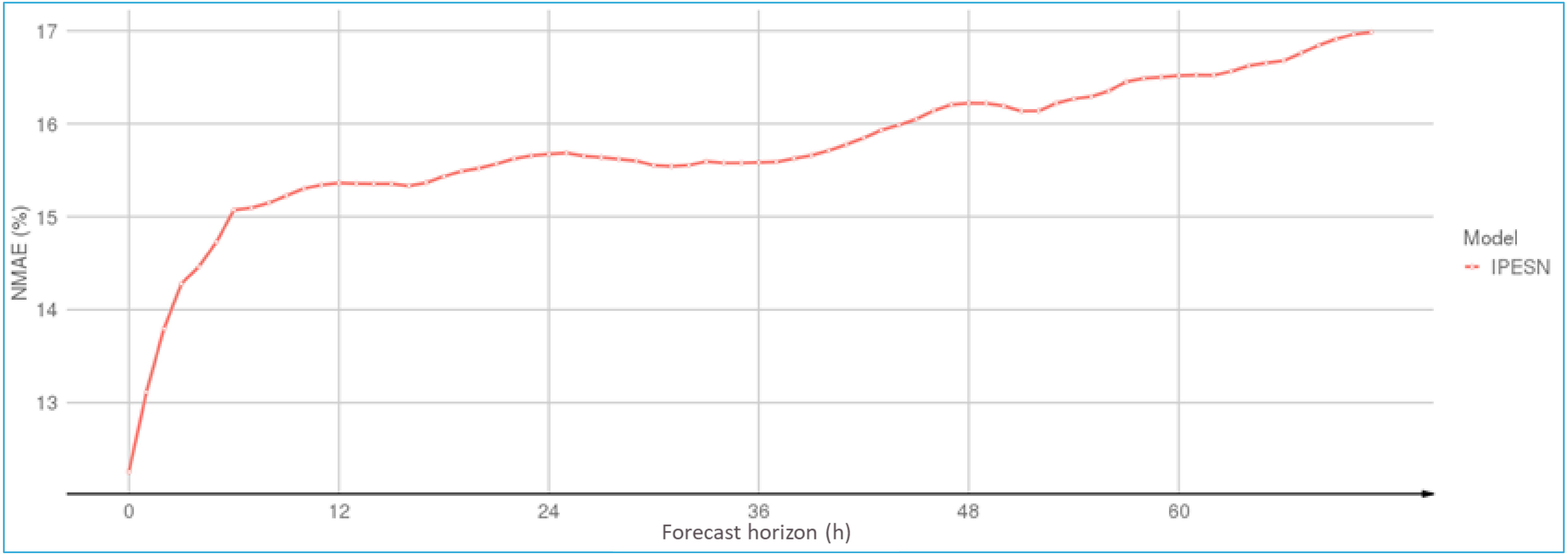


- Photovoltaic average forecast ECMWF ENSEXT France
- Photovoltaic observation France
- Photovoltaic Scenarios forecast ECMWF ENSEXT France
- Photovoltaic seasonal average France

Different types of forecasts

Solar PV: up to 3 days in advance, with significant error beyond 6 hours ahead, which decreases rapidly as real time approaches

Average relative error of solar PV forecasts in 2024 according to the forecast horizon



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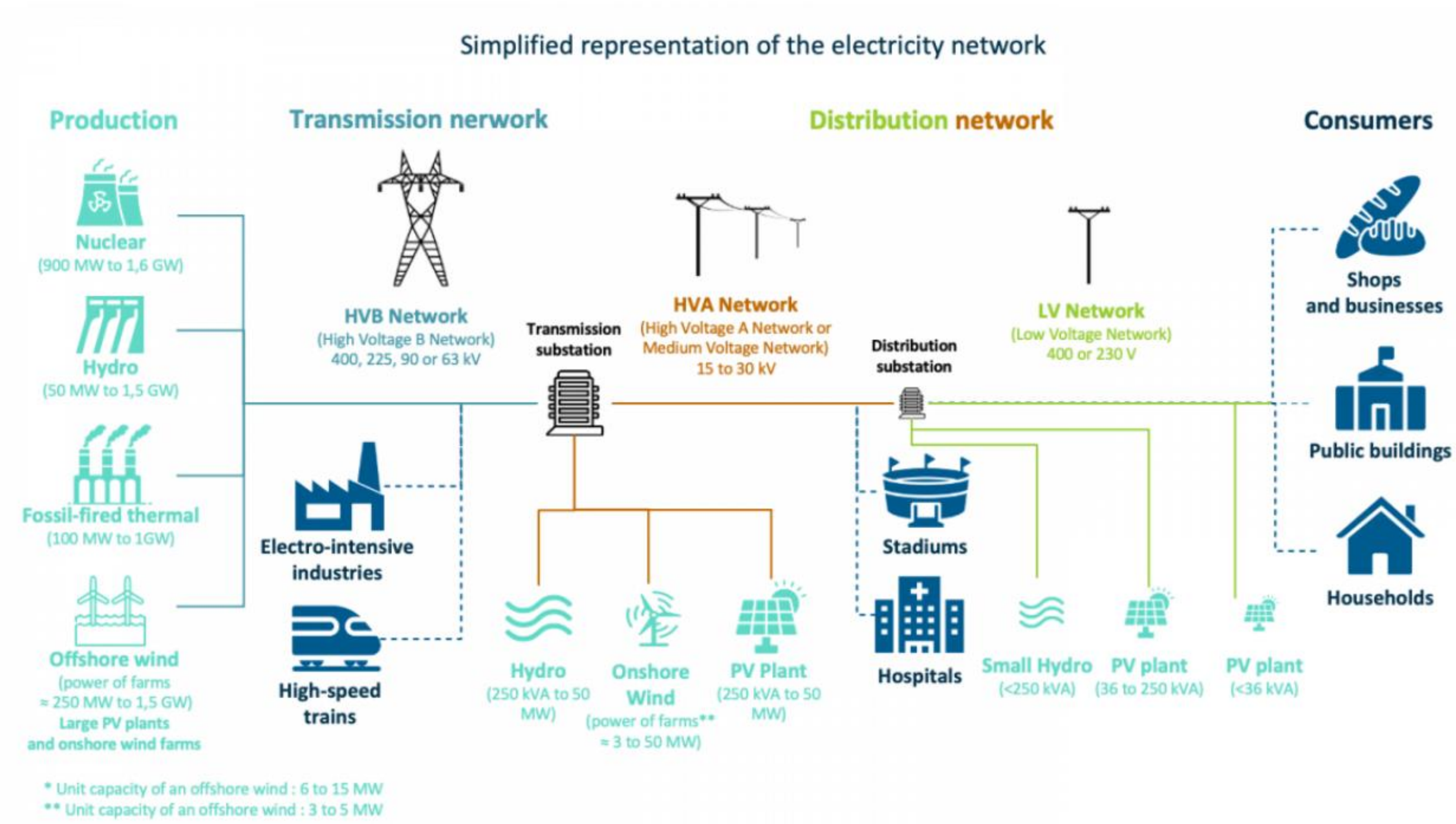
4 AI and the power system management

- *A change of scale of potential actors : from hundreds to millions*
- *Power systems and AI : a long history*
- *The big stake : coordination*

A new paradigm : most of new generation is connected to distribution networks (Medium or even low voltage)



On distribution networks :

53 965 MW

raccordés à la fin du trimestre T3 2025

26 395 (48,91%) / 20 064 (37,18%) / 1 911 (3,54%) / 1 551 (2,87%) / 2 697 (5,00%) / 749 (1,39%) / 598 (1,11%)

1 235 339 installations

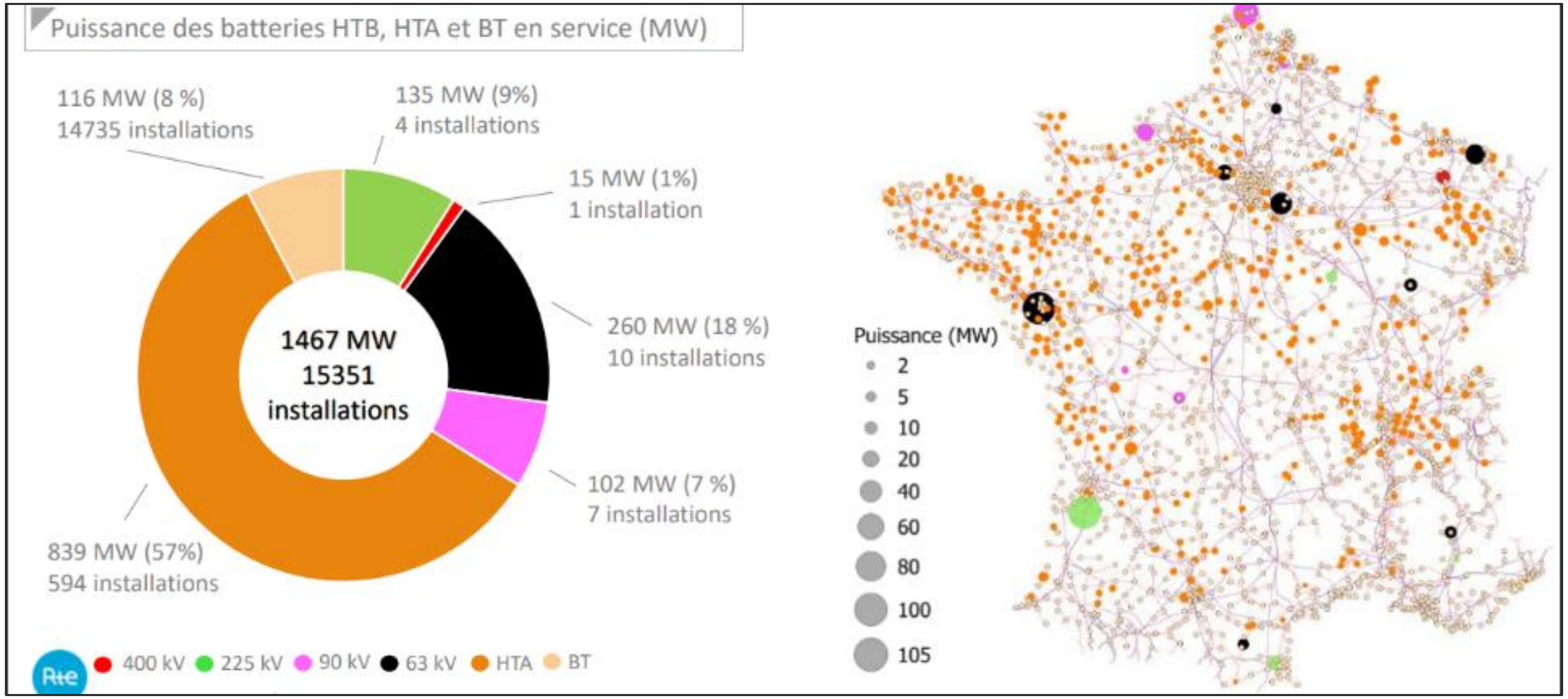
raccordées à la fin du trimestre T3 2025

1 230 295 (99,59%) / 2 248 (0,18%) / 1 158 (0,09%) / 879 (0,07%) / 568 (0,05%) / 191 (0,02%)

Photovoltaïque · Éolien · Hydraulique · Bioénergies · Cogénération · Stockage · Autres

Storage and Distributed consumption will be part of the optimization

Storage :



Consumption :

- 34 M households
- 3 M professionals
- 100k tertiary buildings

Flexible devices :

- 10M water heaters
- 1,5M Evs (expected 10M in 2030)

Power systems and AI : a long history

Power system industry has for decades been one of those using at most applied mathematics :

- Stochastic optimization (for hydro optimization)
- Mixed-integer non linear optimization (for unit commitment)
- Forecasting techniques (for load levels)

Generation portfolio optimization :

For EDF fleet, the non linear MIP problem solving requires 1M variables and 1M constraints.
It mus be done in less than 3 mn

Load forecasting

France has developed tools to manage load dependancy to temperatures for 40 years.
Formerly ARIMA models, now AI machine learning techniques

Power systems and AI : very important perspectives but a big stake which is coordination

1- Forecasting tools

- Important improvements in the recent years for local renewable generation forecasting
- For global forecasting : good performance but need to integrate more information about maintenance and events like negative prices which trigger behavior change

2- Anticipated Decision tools

- Most important decisions are taken in advance, with important uncertainties
- Need for stochastic approaches :
  - Monte Carlo simulations months in advance
  - Probabilistic approaches in the days before

3- Real-time Decision tools

- More deterministic approach
- But appraisal of consequences on the upcoming hours : decision based on time series

4- Coordination tools

- Link between actor decisions, grids and energy markets
- Link between grid management and energy markets (local vs european)
- Link between Transmission System operator and Distribution System operator

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Thank you