



Le réseau
de transport
d'électricité

Uncertainty Matters: Implications for Energy Planning and Power System Resilience

IMPT Workshop on Uncertainty Quantification for Climate Science
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*Thanks to Catherine Lelong, Bénédicte Jourdier, Amaury
Lancelin, Pierre Lefevre (RTE) Youen Kervella (FEM)*

RTE is Europe's leading electricity transmission system operator in terms of network size and investment volume.

Our missions

- Being an industrial operator of a key infrastructure
- Optimizing the operation of the electrical system
- Inform public authorities' decisions on energy issues



10 400 employees
More than 190 sites



€5.56 billion in revenue (2024) €100 billion in planned investments in the network through 2040 to contribute to the success of the energy transition, renew and adapt the network to climate change (2025 Ten-Year Network Development Plan)



100,000 km of overhead power lines and 7,000 km of underground cables, ranging from 63,000 to 400,000 volts, 51 cross-border lines, 3,500 RTE substations at over 2,700 sites, 260,000 pylons 22,750 km of fiber optics



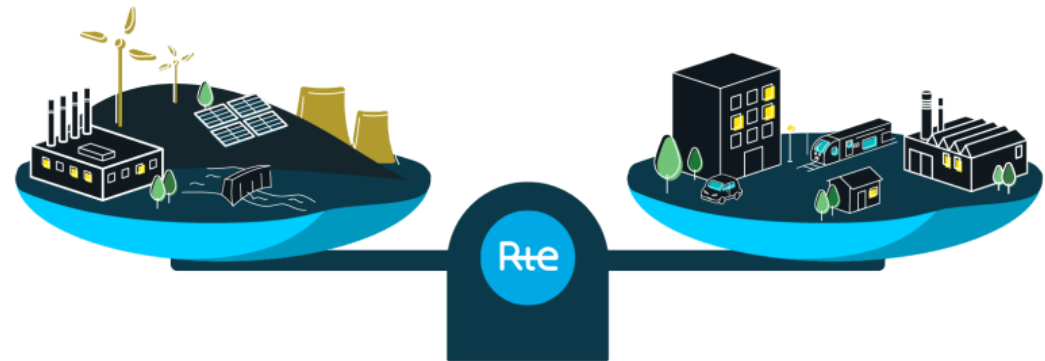
An operator that performs its public service duties within the framework of a monopoly regulated by the Energy Regulatory Commission An operator under the supervision of the DGECA n operator operating in mainland France (excluding Corsica)

The power system is dependent on weather and climate

- Uncertainty is inherent to climate data, models, and simulations — and its influence extends into the decisions made in planning resilient energy systems
- Reliable energy planning requires understanding how uncertainty in climate projections, demand & generation, and infrastructure vulnerabilities affects resource adequacy and system robustness.



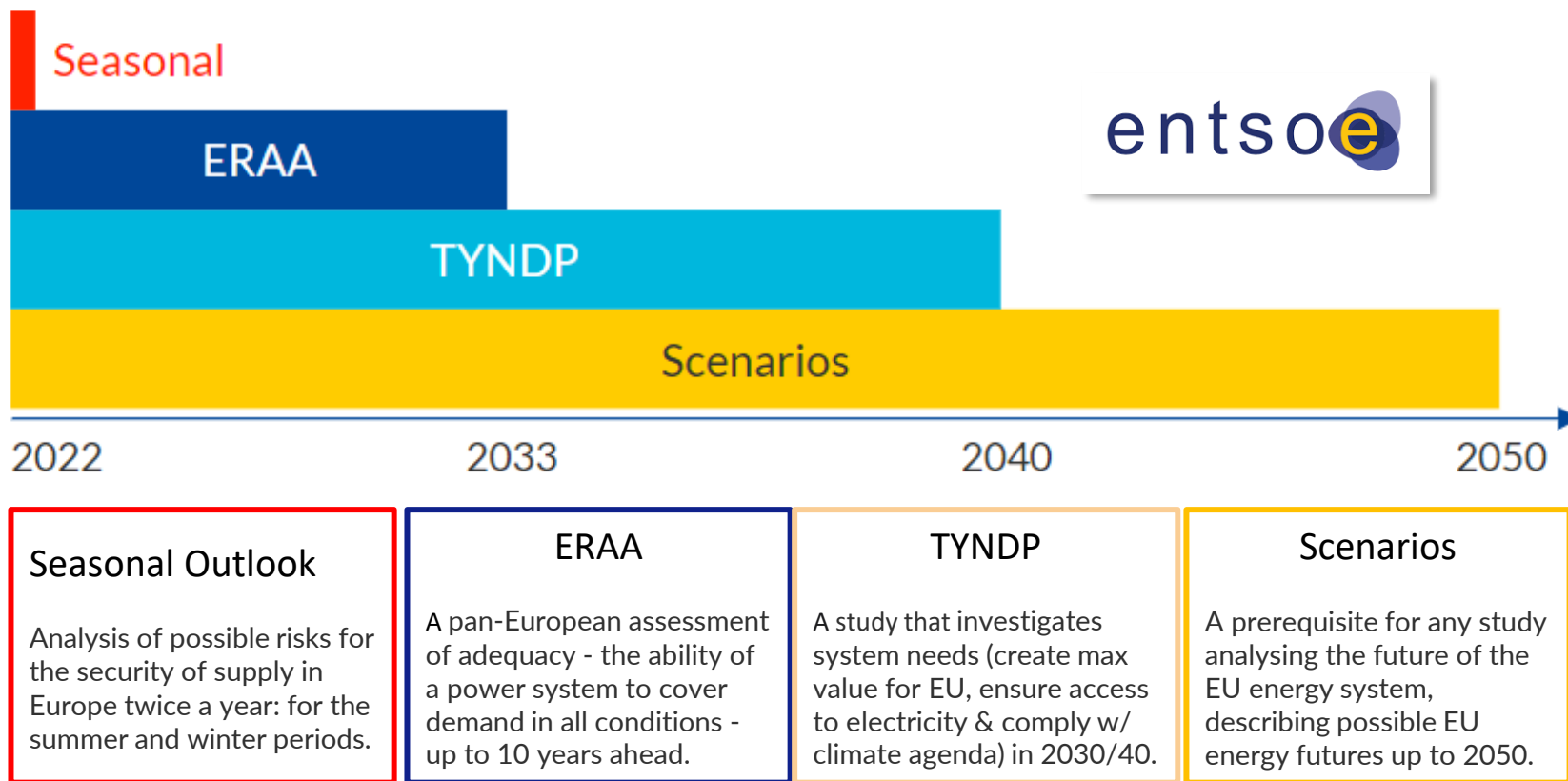
Network RESILIENCE
facing meteorological hazards, *amplified by climate change*



Supply-demand balance (Resource Adequacy)
Renewables' development increases the system dependence on weather and climate



Energy planning?

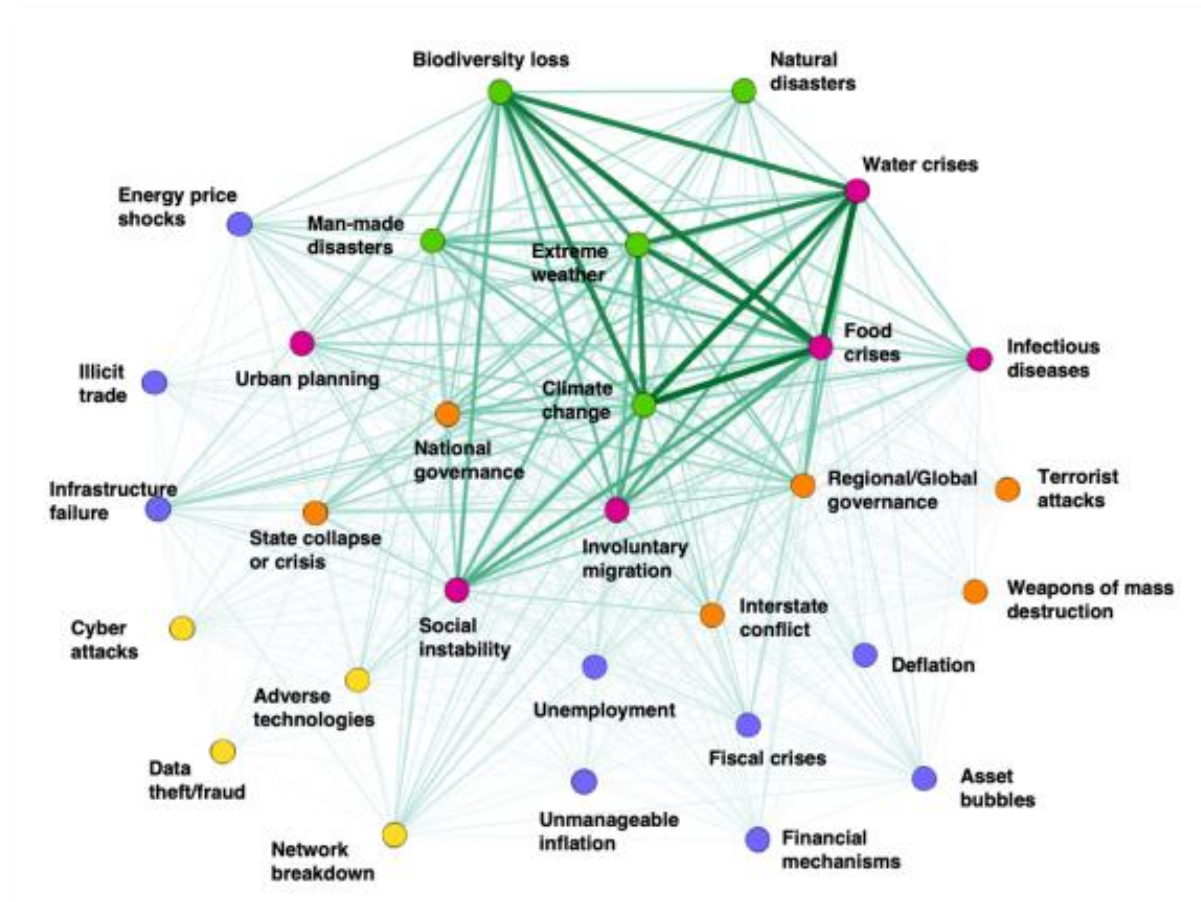


Sources of uncertainty in energy planning



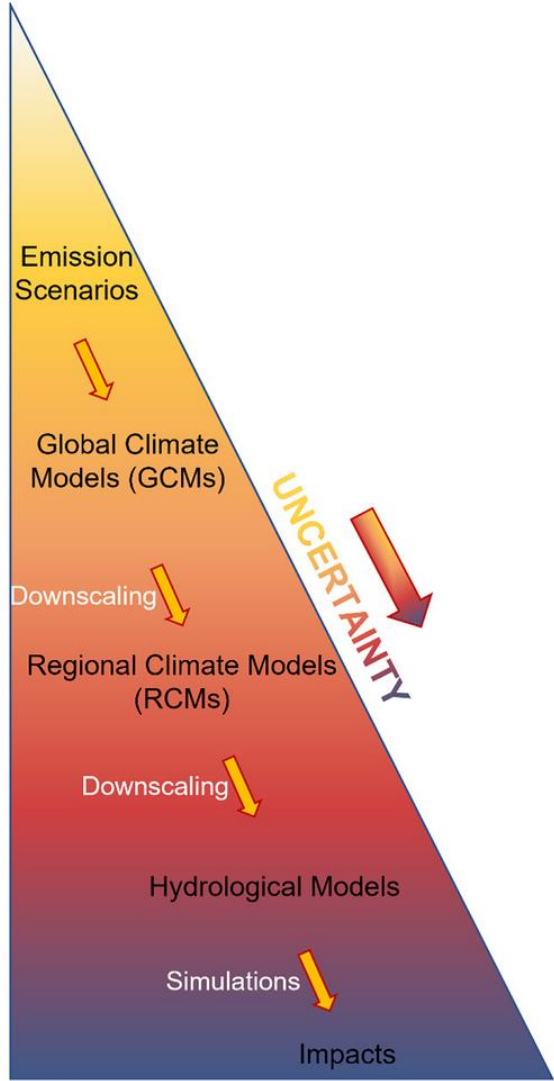
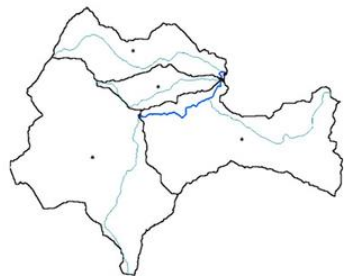
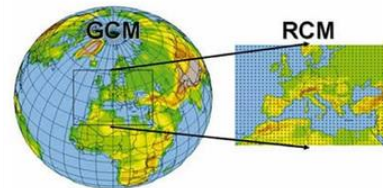
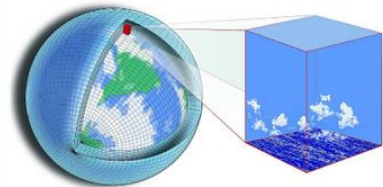
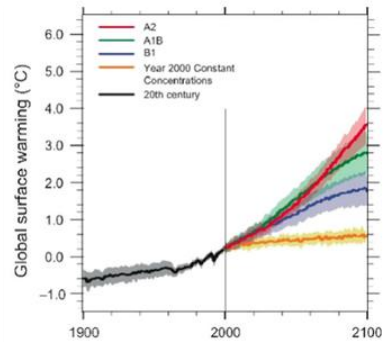
Many **different sources of uncertainty** to take into account:

- **Complexity of Modern Energy Systems**
 - Market fluctuations and economic factors
 - Technological advancements and innovations
 - Social and behavioral factors
 - Policy and regulatory changes...
- **Infrastructure vulnerability:**
 - Ageing & operational constraints add uncertainty to system reliability & performance
- **Climate conditions**
 - Socio economic and emissions scenarios
 - Model uncertainty
 - Natural climate variability
 - Mathematical methods (e.g. extremes)
- **Data quality** (and not only climate data!)

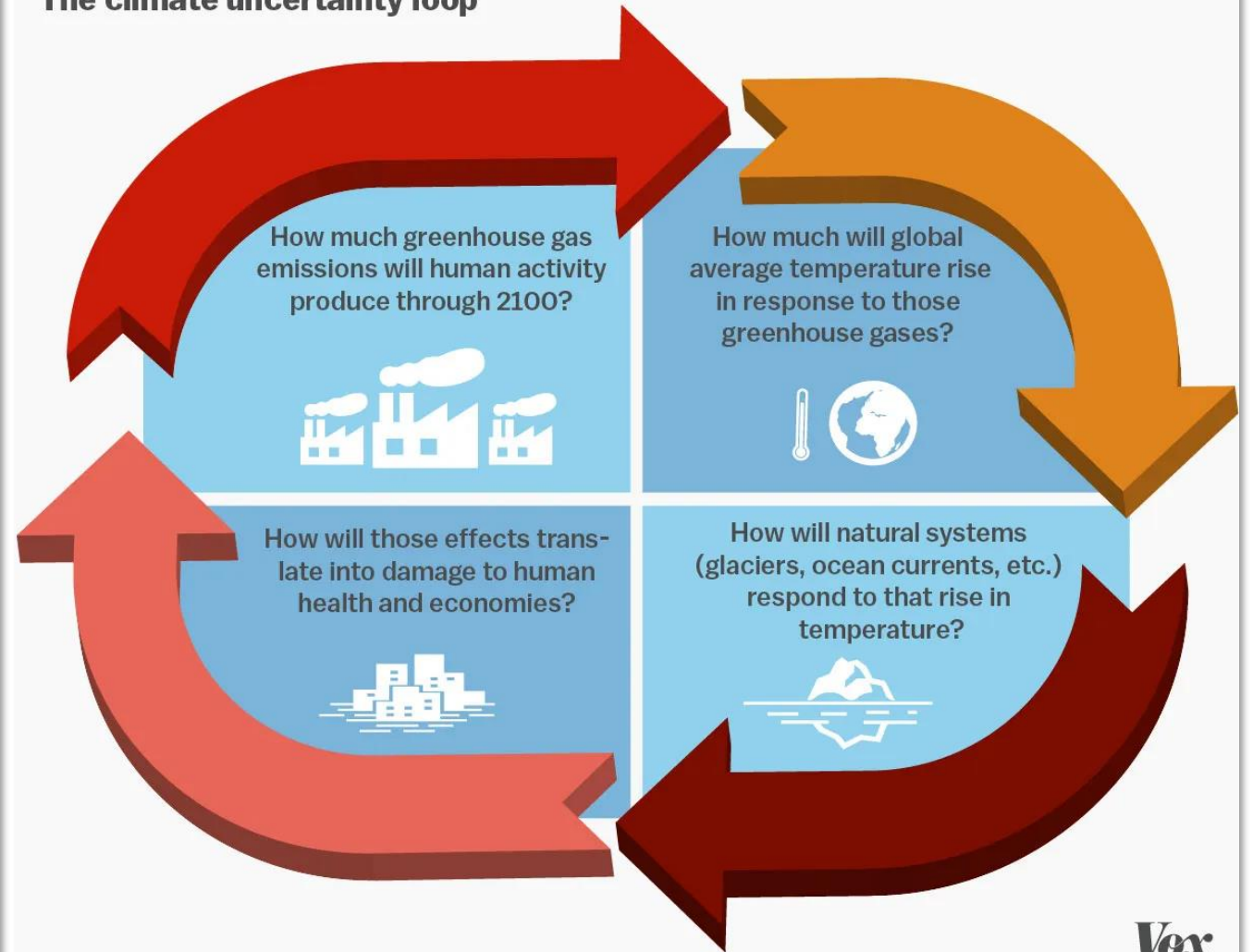


Source: World Economic Forum

Specifically about climate

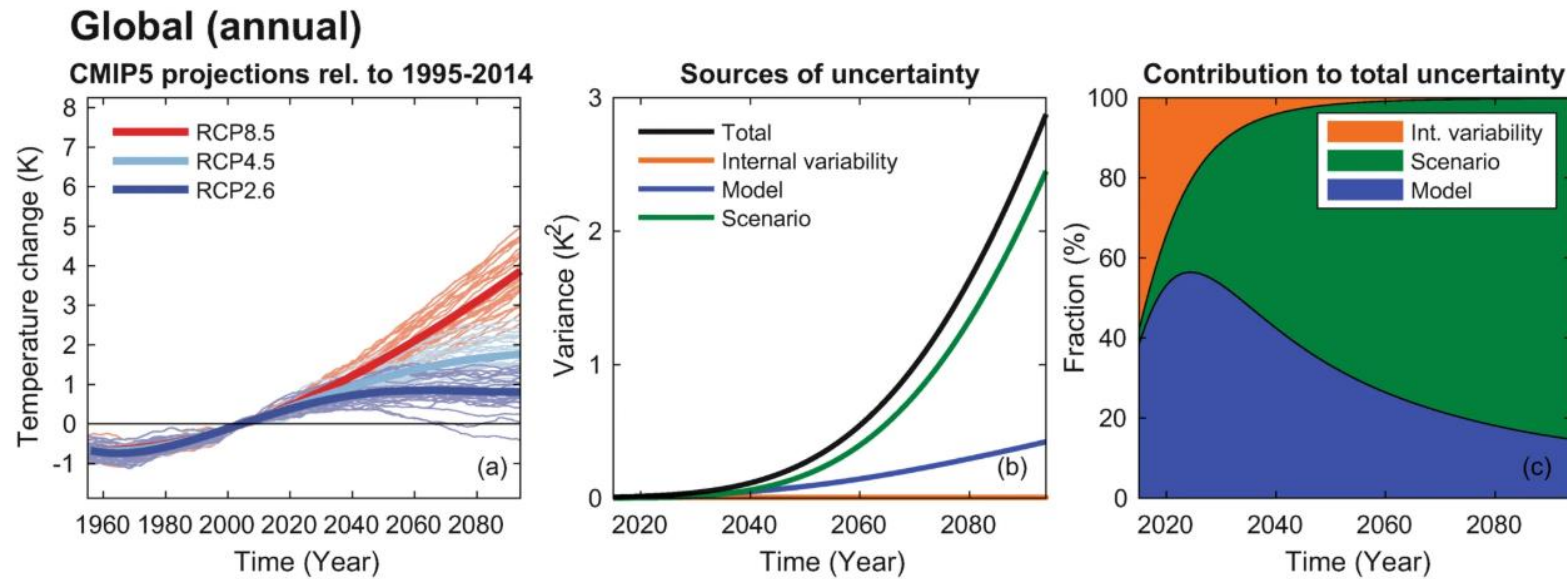


The climate uncertainty loop



Types of uncertainty from the climate side:

- Internal variability (weather vs. climate)
- Model structure differences
- Emissions scenario assumptions



Lehner, F., Deser, C., 2025. https://doi.org/10.1007/978-3-031-85542-9_17



Drivers of demand uncertainty:

- Population growth
- Behavioral factors
- Electrification trends
- Economic/social variables
- Technology adoption (EVs, heat pumps)
- Climate variability and change
- Energy demand models
- etc

Example: Overestimating EV adoption or data centers' growth would lead to overbuilding infrastructure.

→ Implications on capacity planning

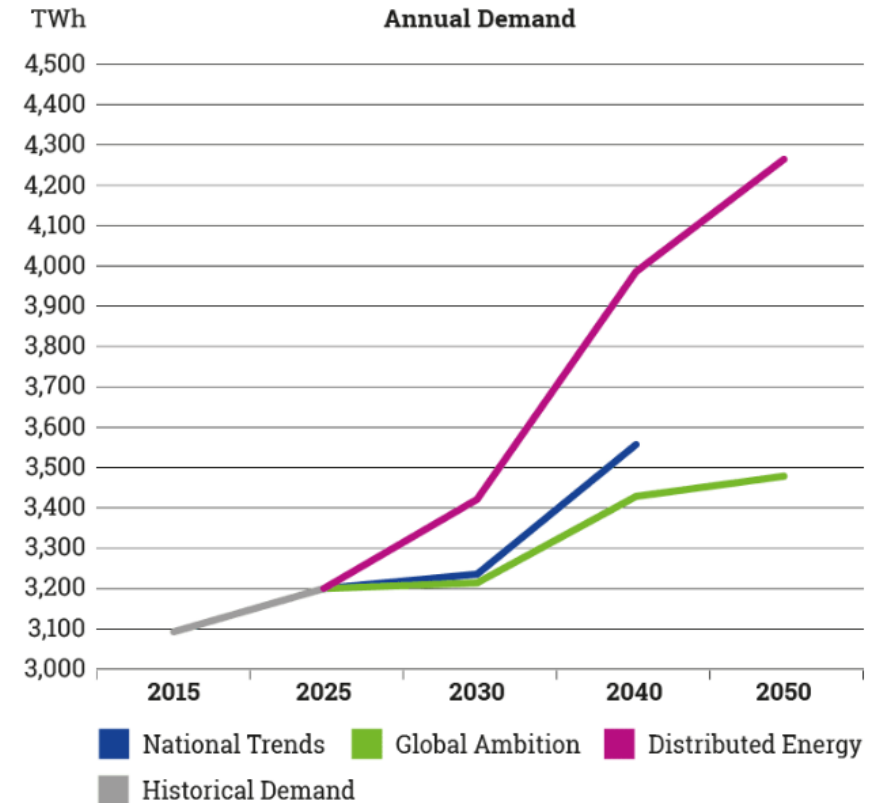


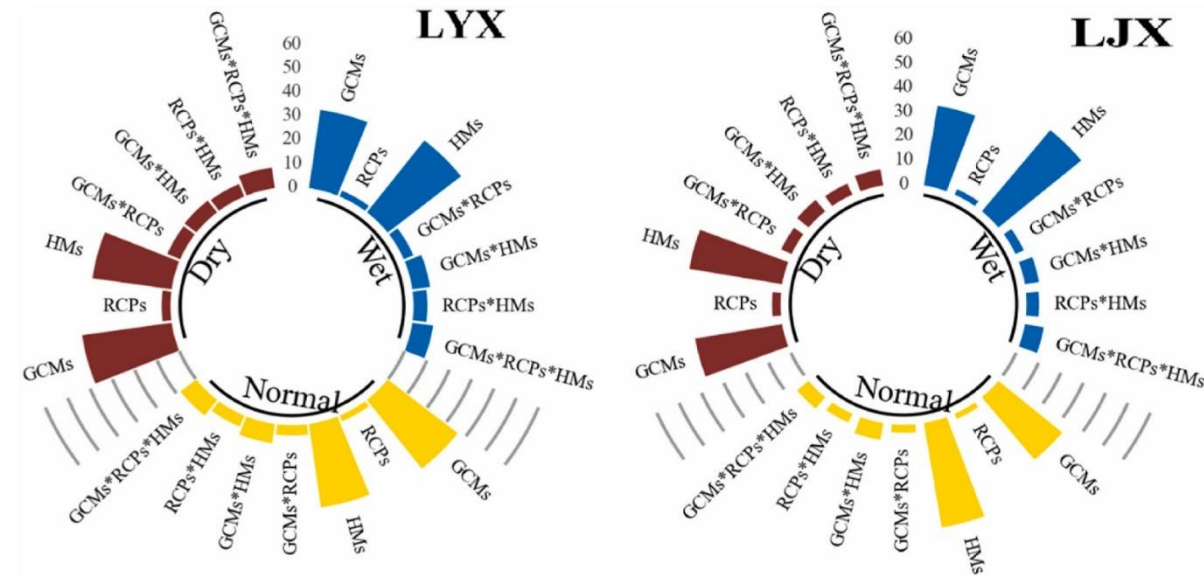
Figure 7: Direct electricity demand per scenario (EU28)

Source: ENTSO-E, TYNDP 2020, [Scenario Results for TYNDP 2020 — ENTSG & ENTSO-E](#)



Impacts on capacity planning and energy generation:

- Cooling/heating demand changes
- Hydropower output variability
- Renewables output variability
- Thermal power units cooling capacity (river flow & temperature)
- Network operating conditions (cables' temperature, power electronics...)



Independent and interactive effects of multiple uncertainty sources on the inter-annual hydropower generation uncertainty with hydrological conditions for 2 different reservoirs. From Zhou et al., 2024, <https://doi.org/10.1016/j.energy.2024.131447>

➔ For each of these a **chain of models/methods** is needed to go from the climate signal to the application

They all come with uncertainties that need to be **understood and quantified**

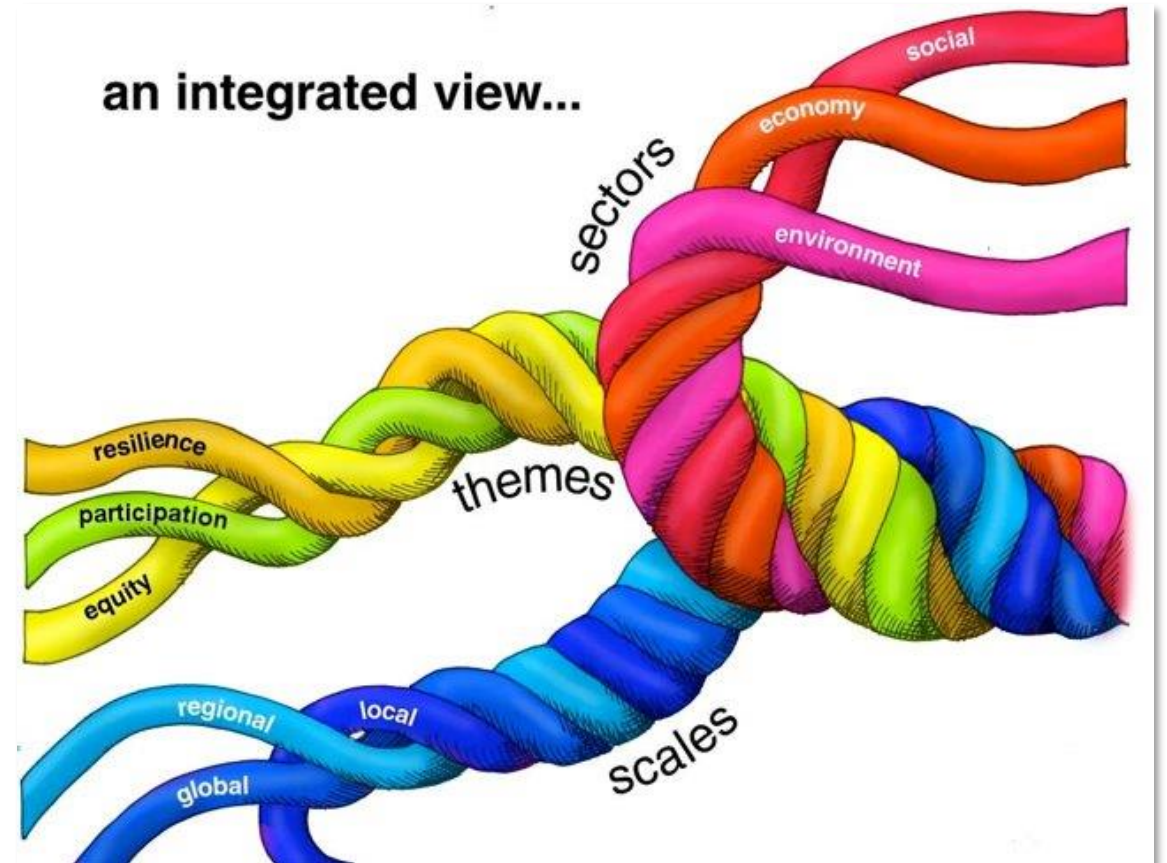
Additional uncertainties arising from:

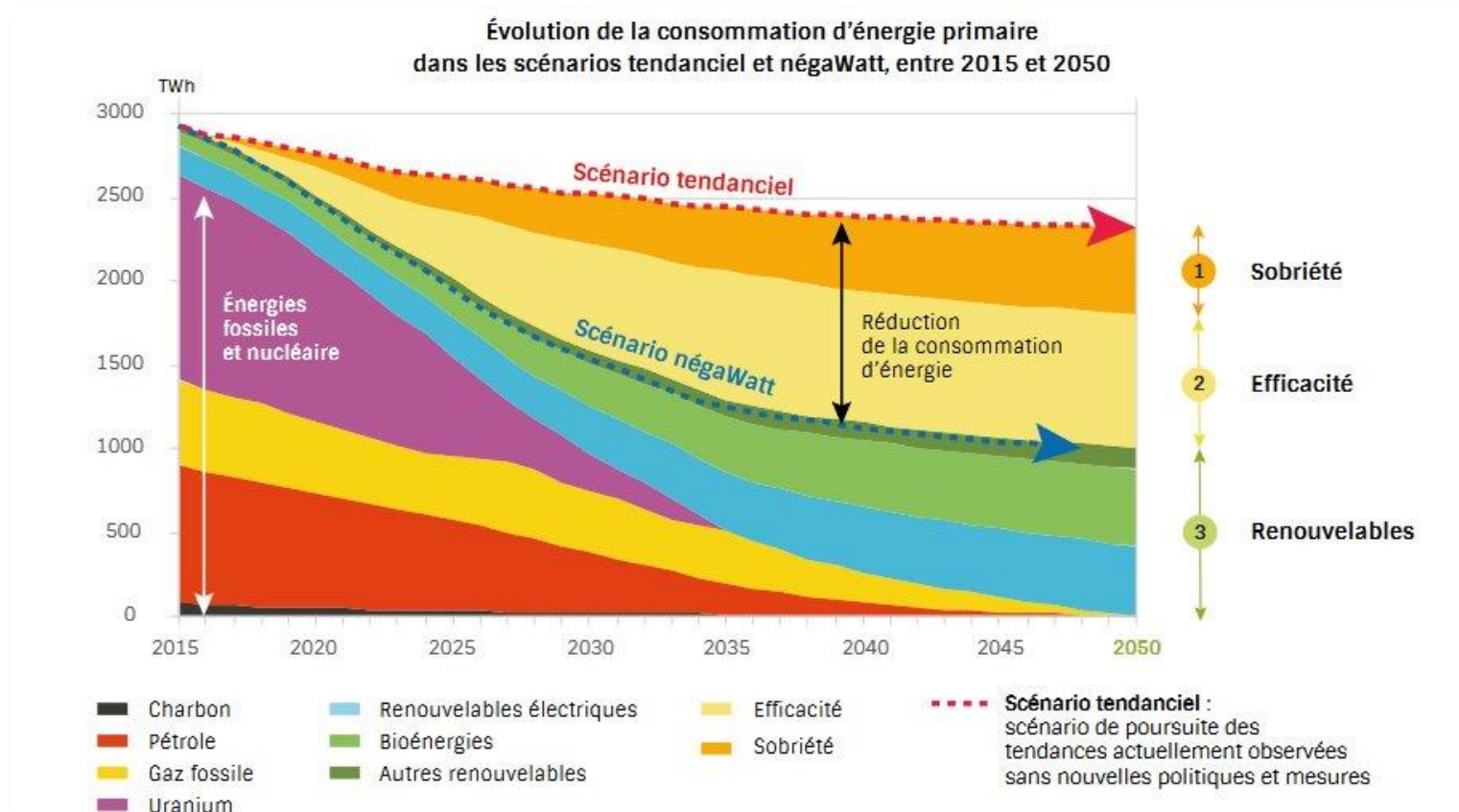
- Technological changes
- Public acceptance of projects
- Geopolitical constrains (materials, supply chains)
- ...

How can we deal with climate uncertainty in power system studies?

**Important : investments are made with public funds.
Optimal design and decision is key!**

- Scenarios
- Classical probabilistic approach : multi-model, multi-scenario, ensembles...
- Sensitivity analysis
- Monte Carlo simulations
- Storylines, stress tests
- ...





Trend scenarios: “no surprises,” continuation of current trends, without major disruptions, and incorporating known factors of change whose probability is certain.

→ Uncertainty is ignored

Ex: business as usual scenarios

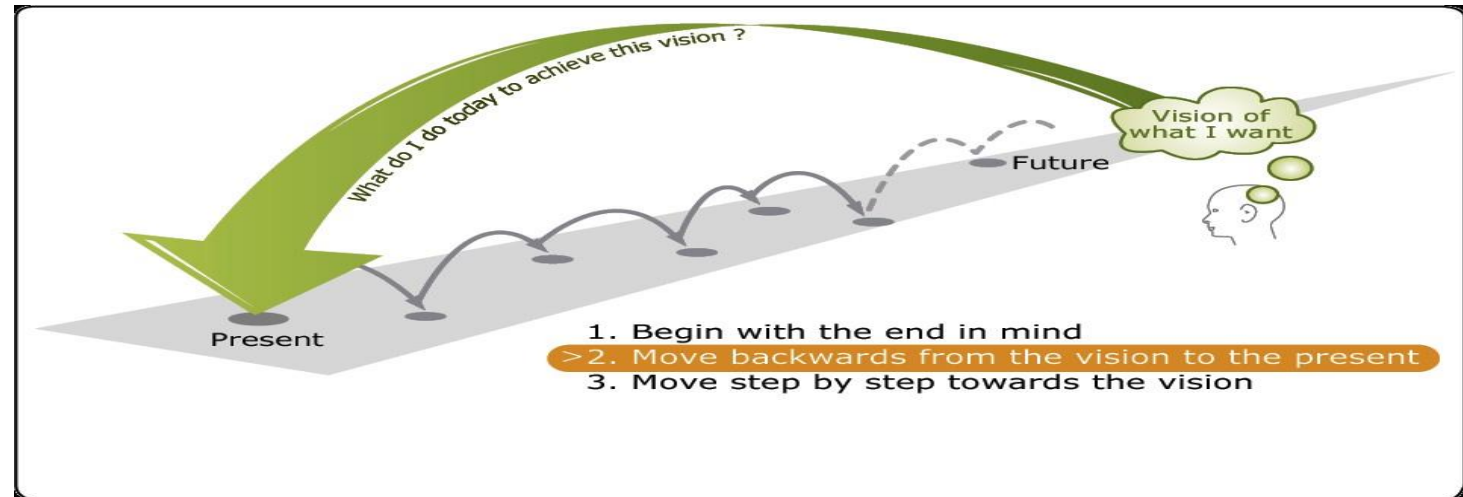
Exploratory / contrasting scenarios (forecasting): exploration of possible futures based on a known initial situation

Ex: IEA long-term scenarios, ENTSO-E 2050 scenarios, *IPCC SSPs*

Allows to fix some variables and get rid of some uncertainties

Normative scenarios (backcasting): path from the future to the present based on a desirable future, the means to be implemented to achieve defined objectives

Example: EU's Zero net emissions in 2050



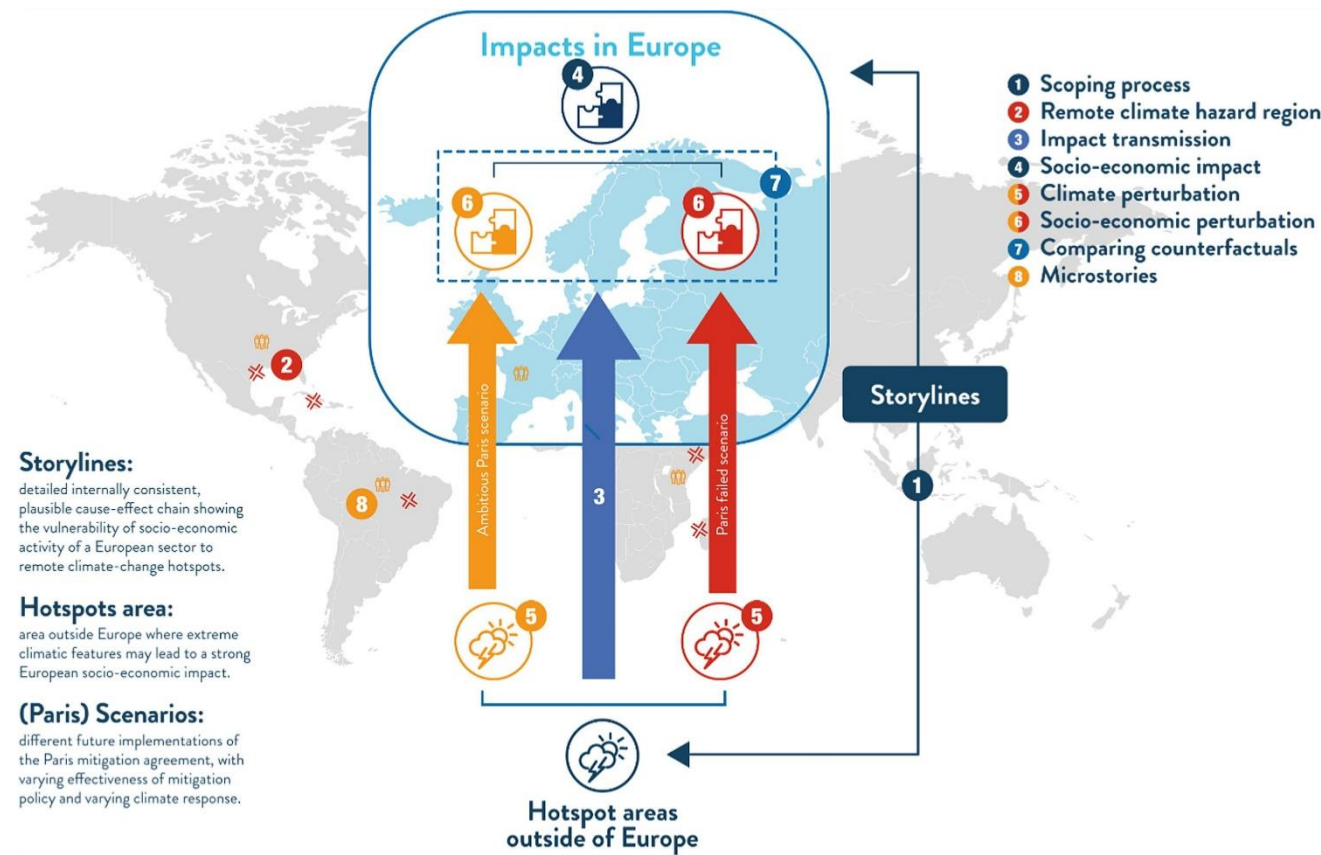
Storyline are “a physically self-consistent unfolding of past events, or of plausible future events or pathways. No a priori probability of the storyline is assessed; emphasis is placed instead on understanding the driving factors involved, and the plausibility of those factors.”

(Shepherd et al., 2018 <https://doi.org/10.1007/s10584-018-2317-9>)

They can:

- ➔ Raise awareness
- ➔ Provide an effective mechanism for strengthening decision-making
- ➔ Provide a physical basis for partitioning uncertainty
- ➔ Explore boundaries of plausibility

Eventually, they can help better define **stress-tests** of a given complex system



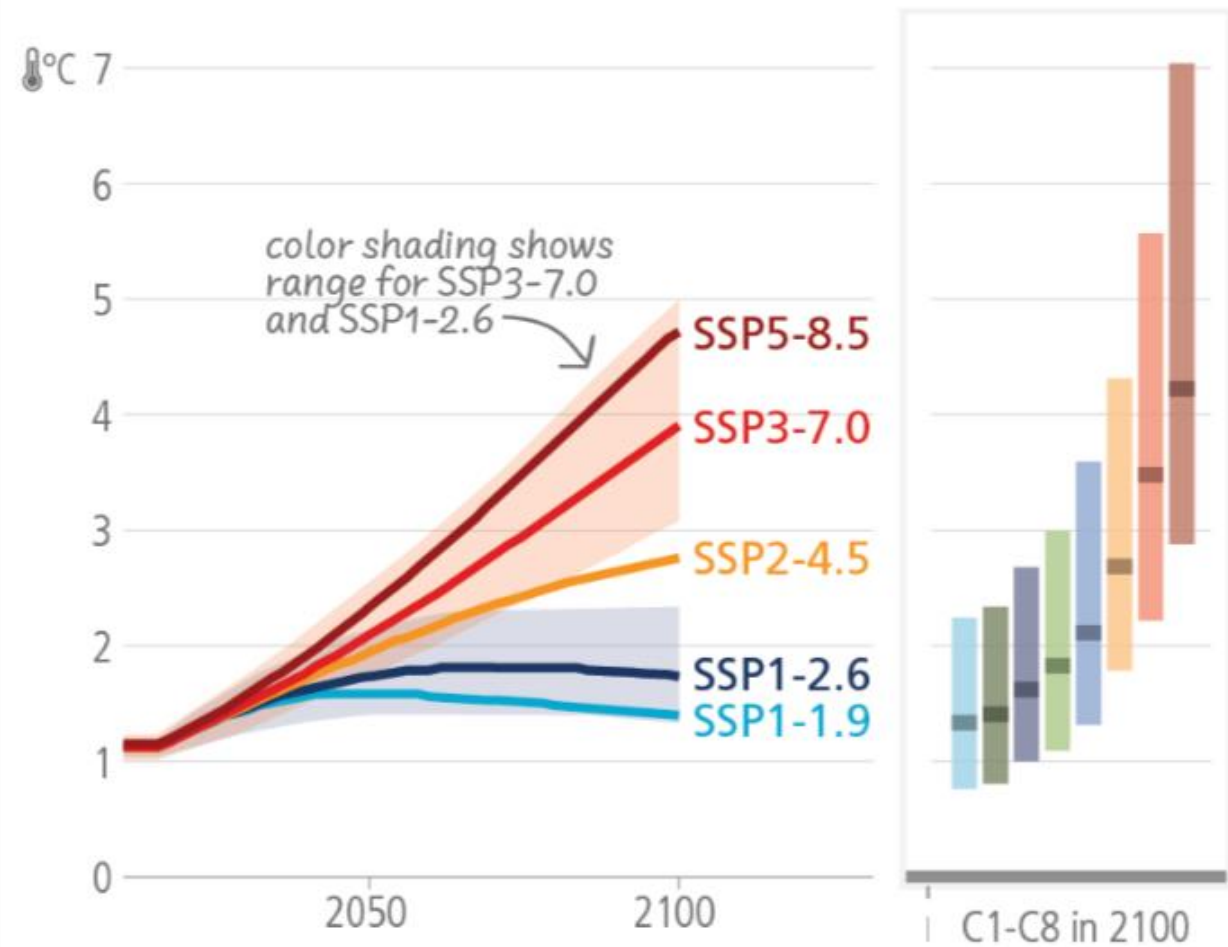
Van den Hurk et al., 2023 <https://doi.org/10.1016/j.crm.2023.100500>



The « classical » climate uncertainty

Source: IPCC AR6 synthesis report

Temperature for SSP-based scenarios over the 21st century and C1-C8 at 2100

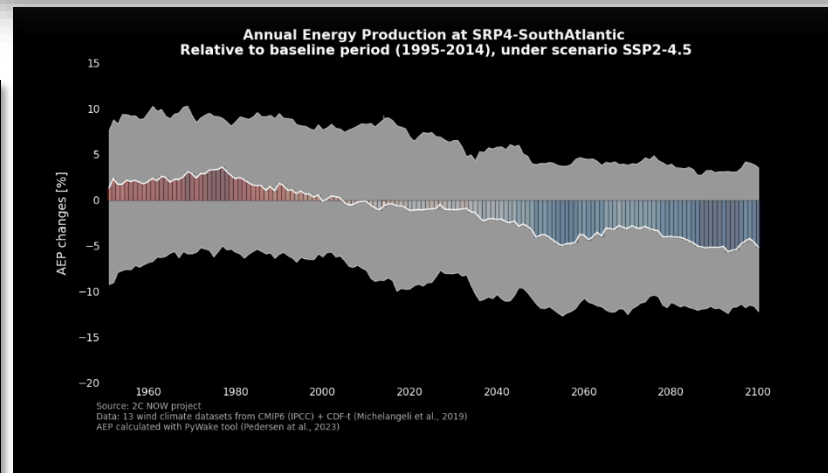
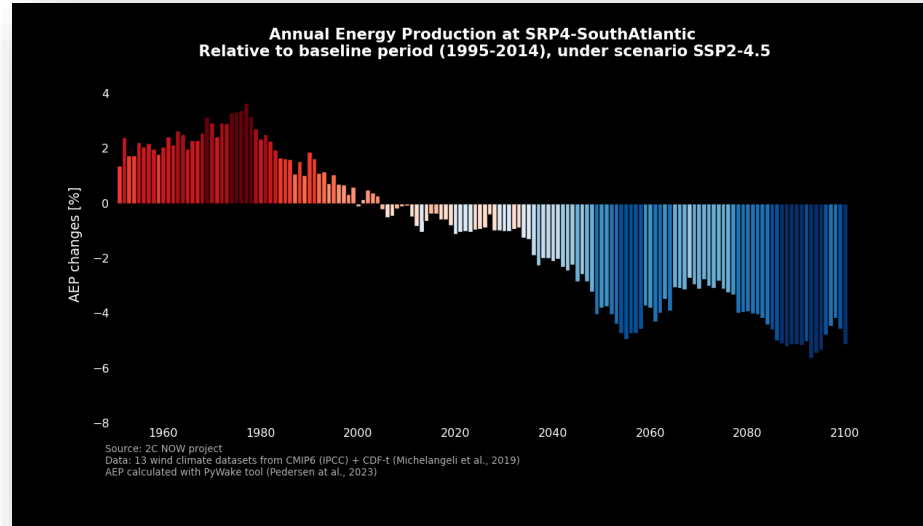


Standard multi-model/multi-scenario approach

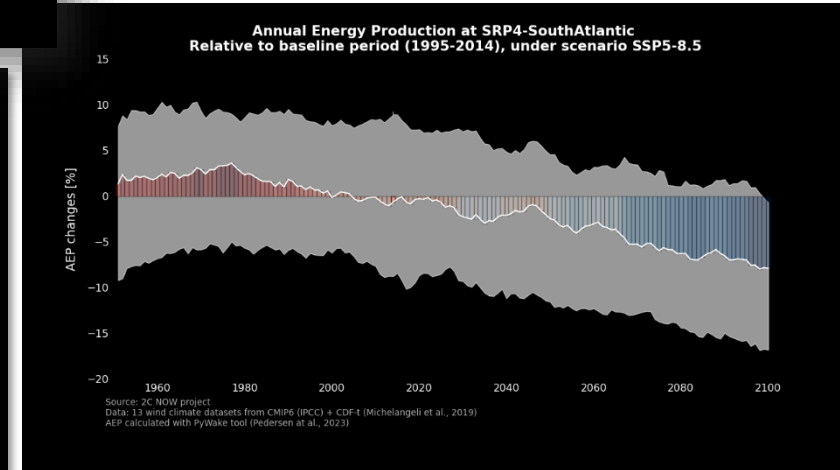


Results from the **2C NOW**
Joint Industry Project

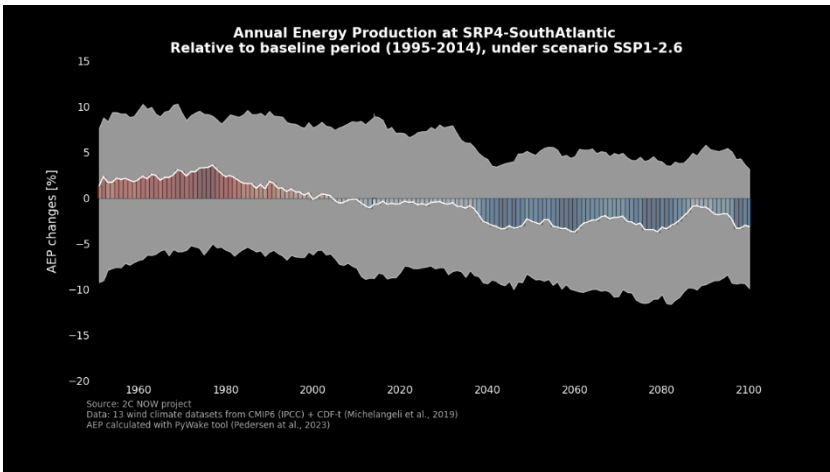
13 CMIP models



SSP2-4.5



SSP5-8.5



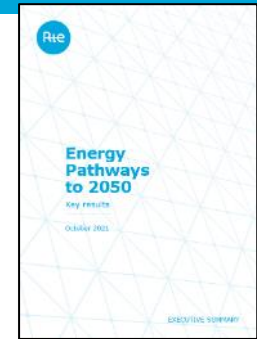
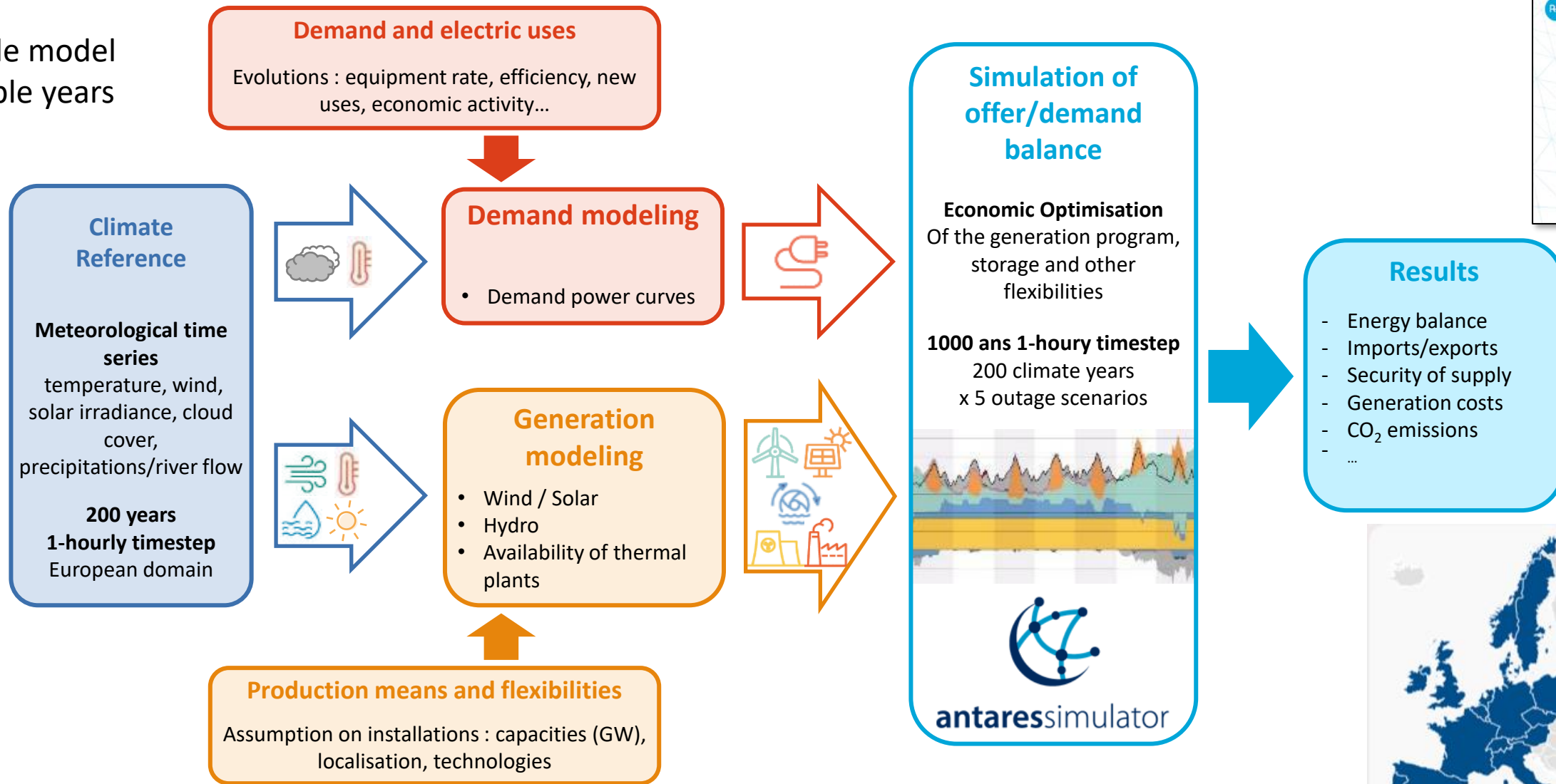
SSP1-2.6



Climate uncertainty in long-term adequacy studies: Monte Carlo simulations



1 single model
Multiple years



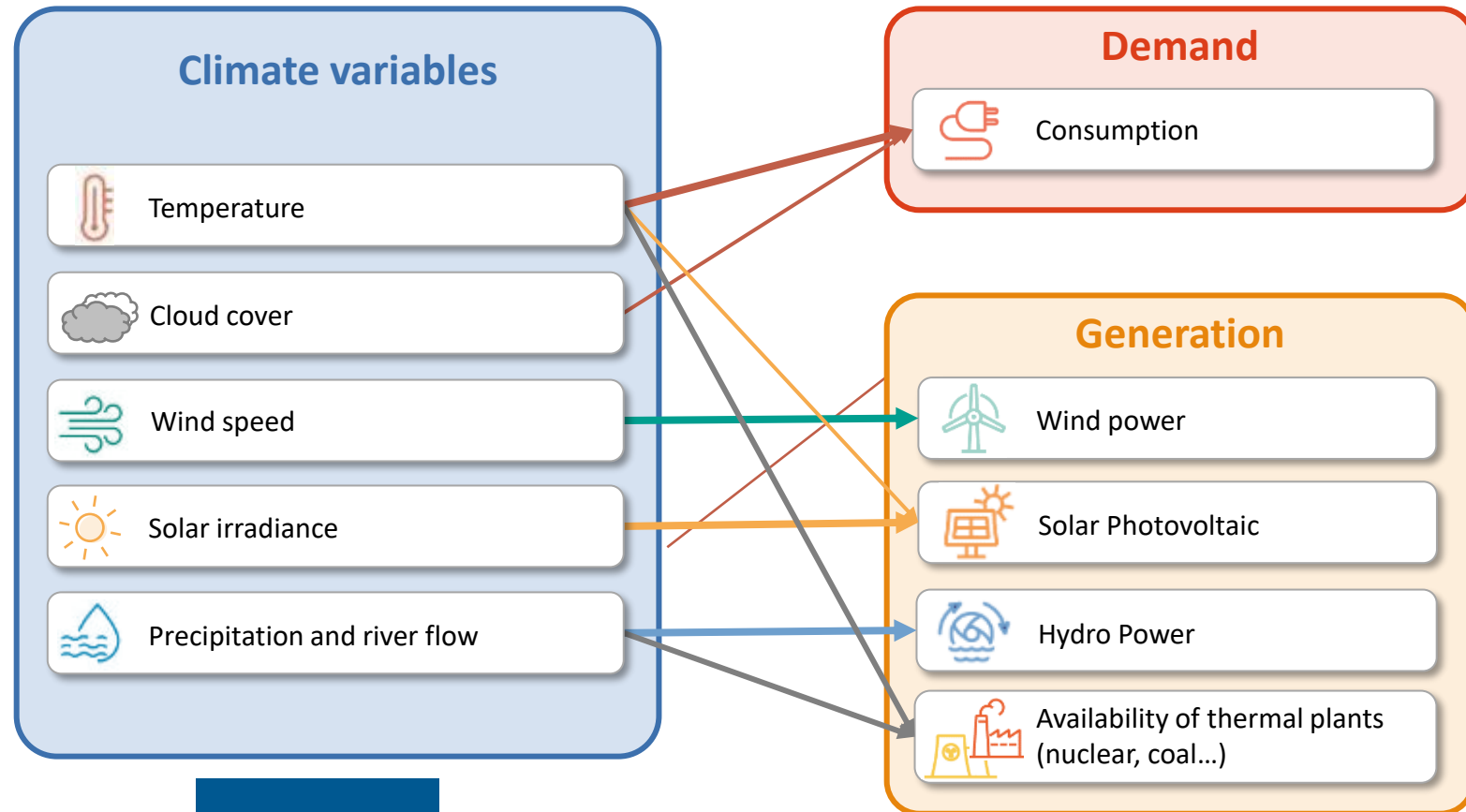
Climate modeling at RTE, previous approach



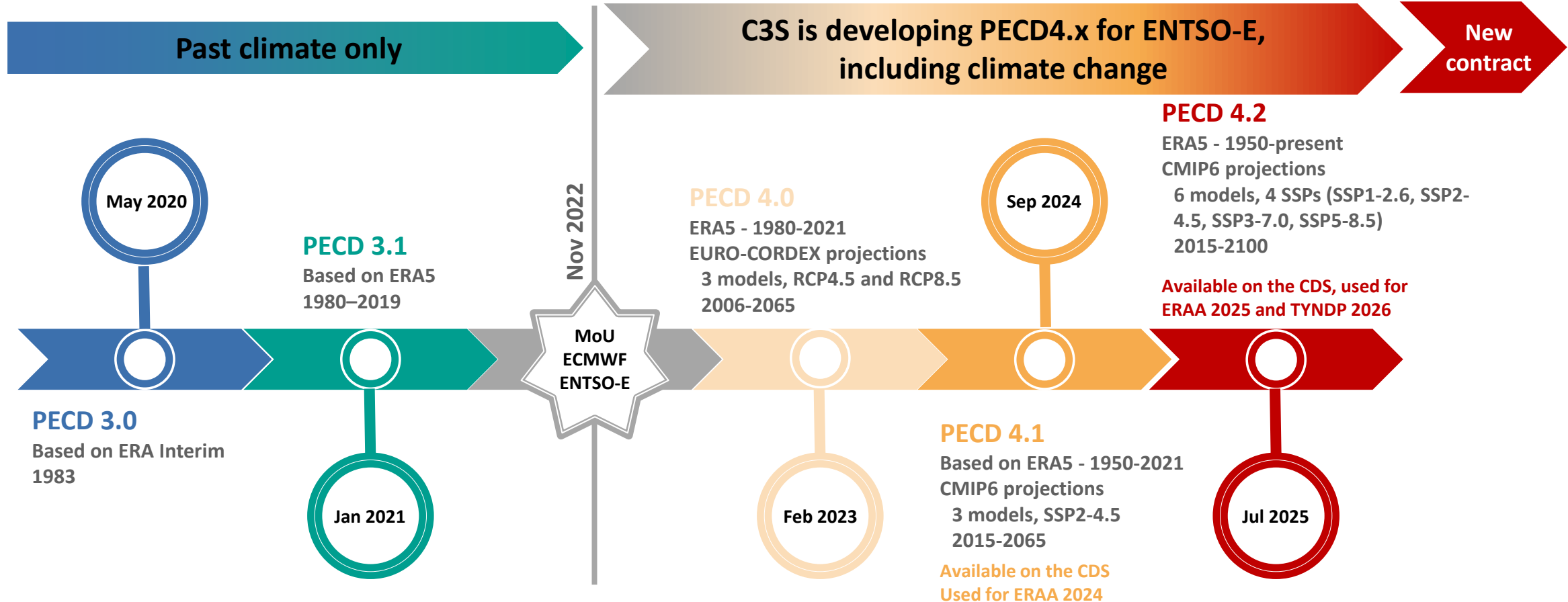
- Dedicated climate simulations provided by Météo-France, based on ARPEGE Climat v5 (CMIP5)
- So-called « constant climate simulations »
- Representing **3 different climates** :
 - **Climate 2000s**
 - **Climate 2050s – RCP 4.5**
 - **Climate 2050s – RCP 8.5**

For each simulation set

- 200 fictives years (fictives) with 1-hourly timestep
- All over Europe
- All variables necessary for power systems simulations



New approach: the Pan-European Climate Database







Funded and led by

Climate Change Service

Developed by







Meteorological variables

-  Temperature
And population-weighted temperature
-  **Wind speed at 10 m and 100 m**
-  **Precipitation**
-  **Global radiation** at ground level
(No cloud cover)

25km resolution grid
& **data aggregated by zone** (country, market zone and PECD zone)



Energy variables

-  **Onshore wind:** load factors for 10 technologies
 - Current fleet (at end of 2020)
 - Future fleet: 3 hub heights x 3 technologies (→ 9 combinations)
- Offshore wind:** load factors for 3 technologies
 - Current fleet (2020)
 - Future fleet: 2 technologies (155 m hub height)
-  **PV:** load factors for 4 technologies (residential roofs, industrial roofs, ground-mounted plants and single-axis trackers)
-  **CSP:** concentrated solar power plants (with/without storage)
-  **Hydropower:** energy contributions for 4 technologies (run-of-river, pumped storage, reservoirs and open STEP)

Data aggregated by zone (countries, market zones and PECD zones)

1950

Present



2015



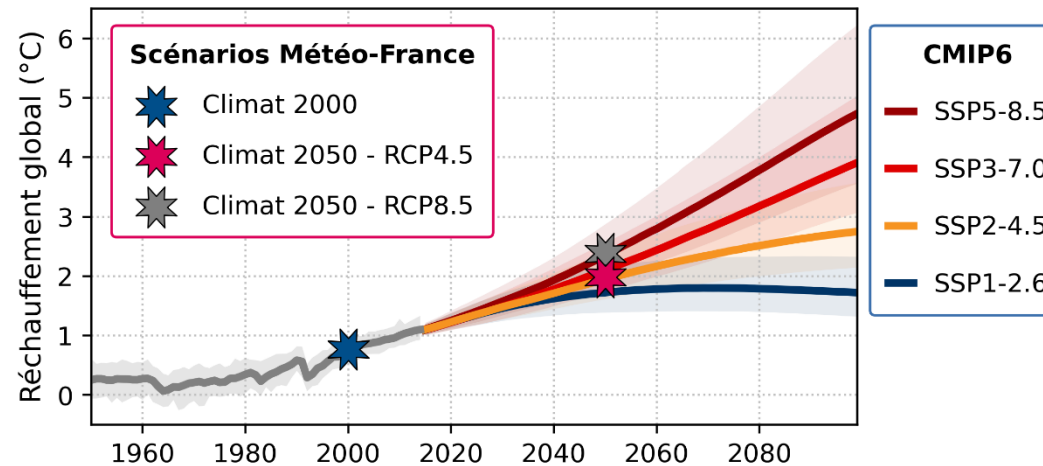
6 climate models (CMIP6)
SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios

2100



Météo-France constant climate scenarios

- ❖ Past re-runs: 1980–2018 (no updates)
- ❖ Future simulations
 - 1 model only
 - 3 "constant" climates
 - 200 years for each



PECD 4.2 (Pan-European Climate Database)

- ❖ Past re-runs: 1950 – present [M – 2]
- ❖ Future simulations
 - 6 CMIP6 models
 - 4 emission scenarios (SSP)
 - 2015–2100 (years to be selected according to the time horizon)

- ❖ Weather variables
- ❖ Renewable energy variables calculated by RTE:
 - statistical models without technological developments

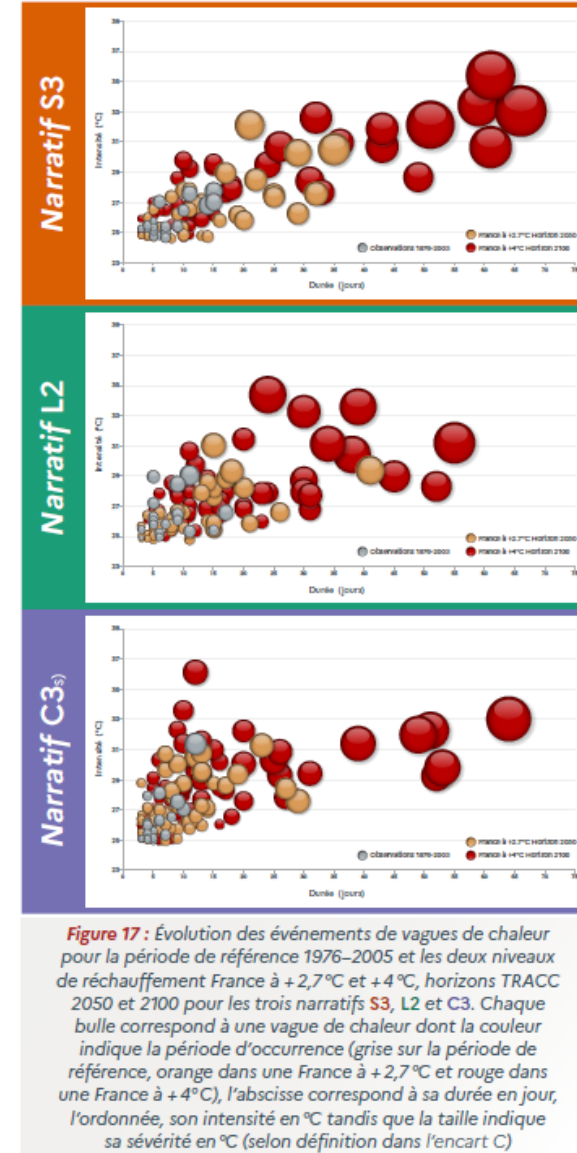
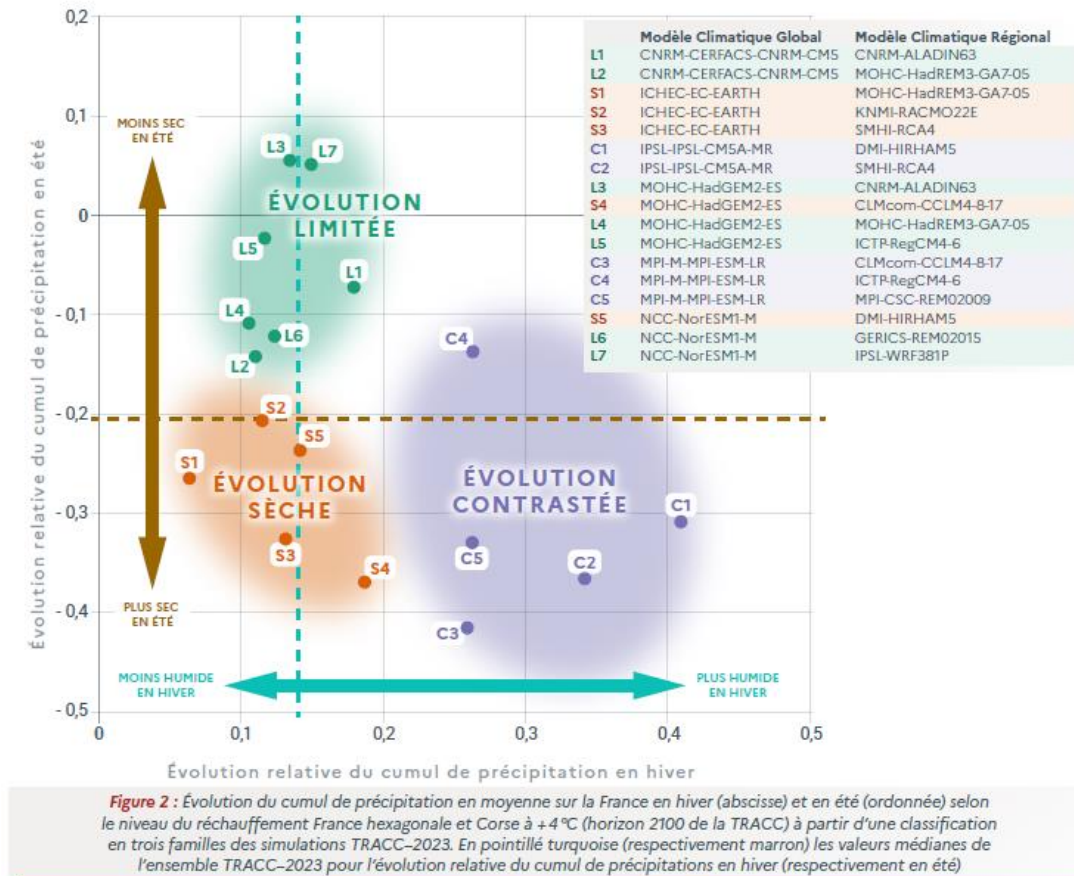
- ❖ Weather variables
- ❖ Renewable energy variables already calculated:
 - ✓ Wind FC for existing + 9 technologies (zonal grid)
 - ✓ PV CF for 4 technologies (zonal grid or 25 km grid)
 - ✓ Hydraulic inputs (national grid only)

→ A better approach, by using more models, more scenarios and time gap-free simulations
 → SSP2-4.5 as a reference + sensitivity analysis

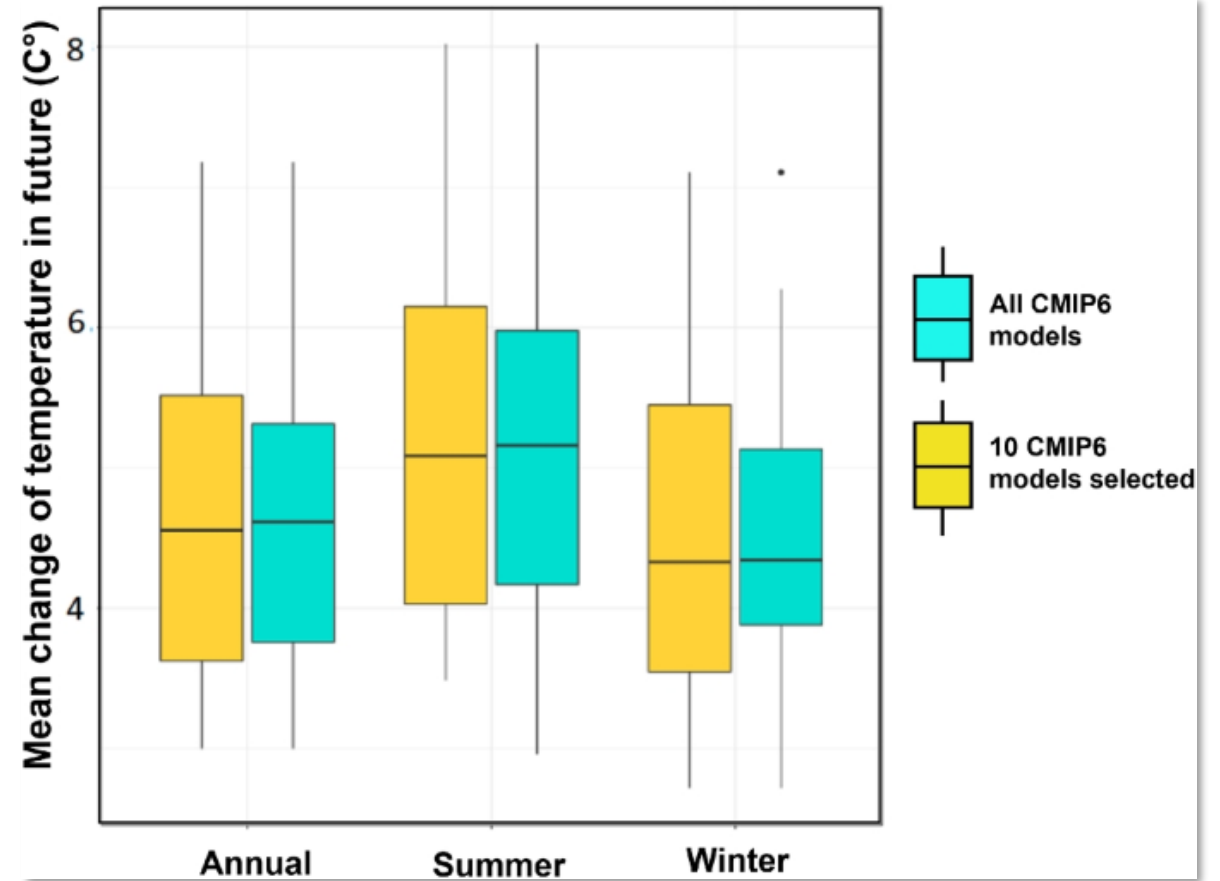
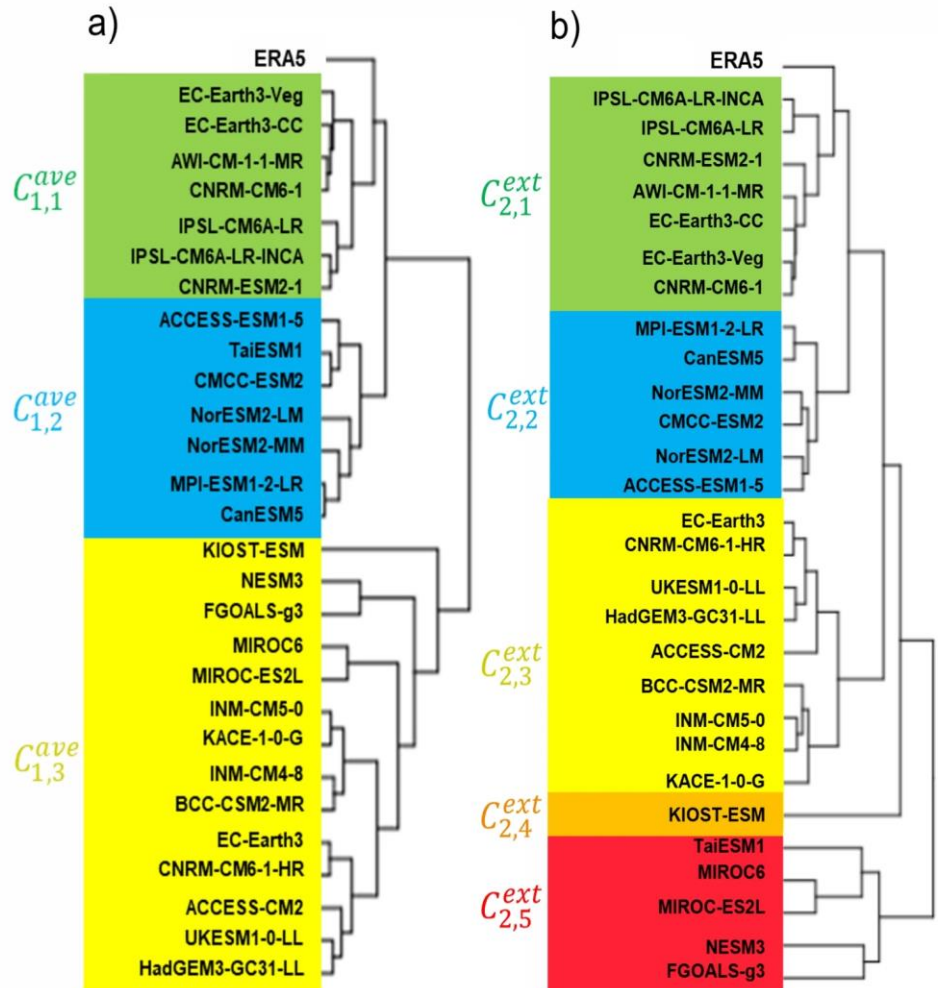
When computing time or capacity is limited?

Optimal selection of climate models or climate years subsets: narrative approach

In case of limited simulation capacity:
How to select representative members?



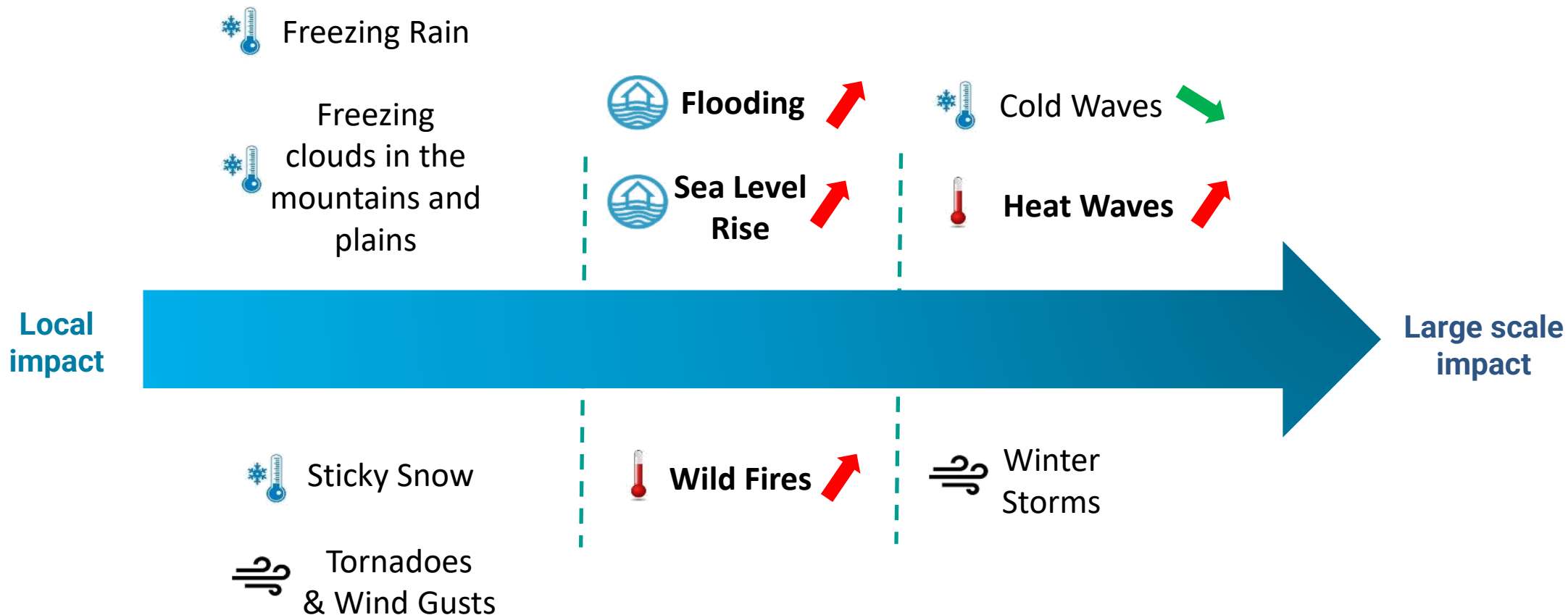
Optimal selection of climate models or climate years subsets: hierarchical clustering approaches





RESILIENCE

Impacts of climate change on existing and future assets



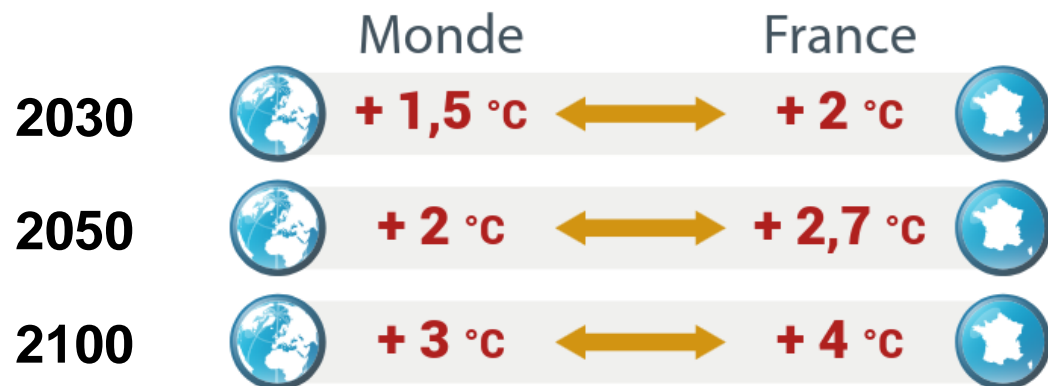
Priorities led by geographical extent of the risks, robustness of the signal (uncertainties), and criticality of impacts



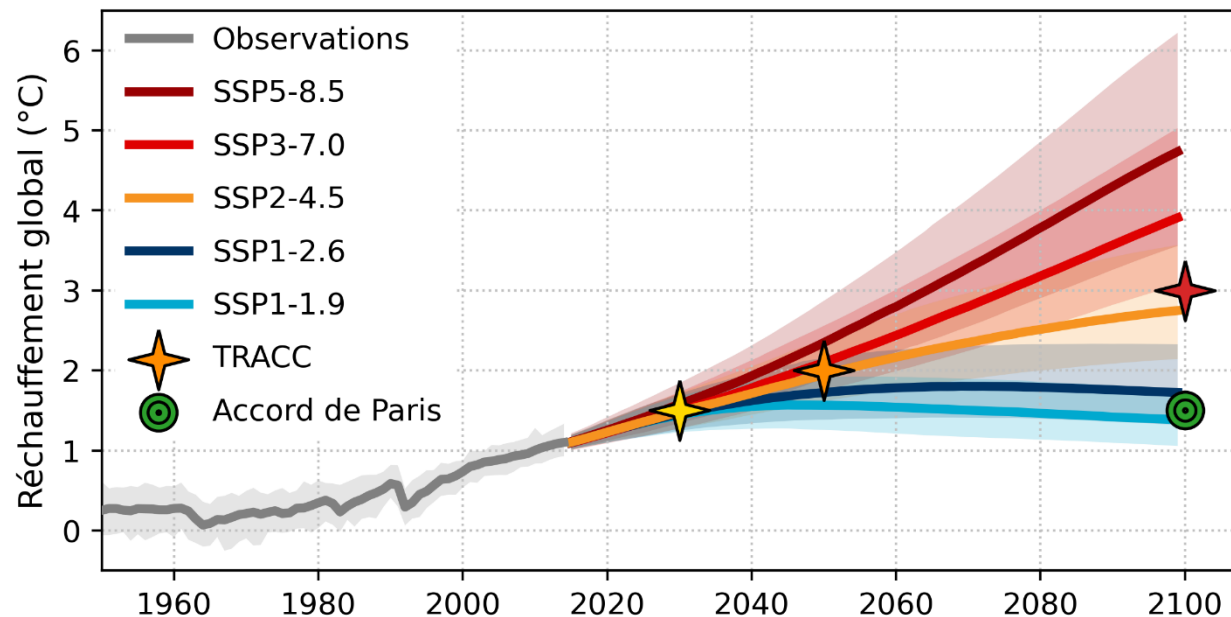
Sizing of assets must be done to cope with extremes

Considering worst case scenarios (e.g. SSP5-8.5) can lead to over-investment and very high costs, with a risk of no action due to political blocking or citizens' opposition

Political guidance and regulation can help determine the targets: TRACC in France.



Changement de température moyenne mondiale par rapport à 1850-1900. Modèles CMIP6 : moyenne et intervalle de confiance [5%-95%] par SSP.



Integrated Approaches to Energy Planning

But guidance remains fuzzy and lacks methodological support
So uncertainties remain

Jour le plus chaud de l'année (°C)	1976–2005	France à +2°C	France à +2,7°C	France à +4°C
Lille	32	33 [31;35]	34 [32;36]	37 [35;40]
Paris	34	36 [34;38]	37 [35;39]	40 [38;42]
Brest	30	31 [30;33]	33 [31;35]	34 [33;37]
Lyon	33	36 [34;38]	37 [34;39]	40 [38;43]
Toulouse	35	38 [36;39]	39 [37;40]	41 [40;43]
Marseille	35	37 [35;38]	38 [36;39]	40 [38;42]

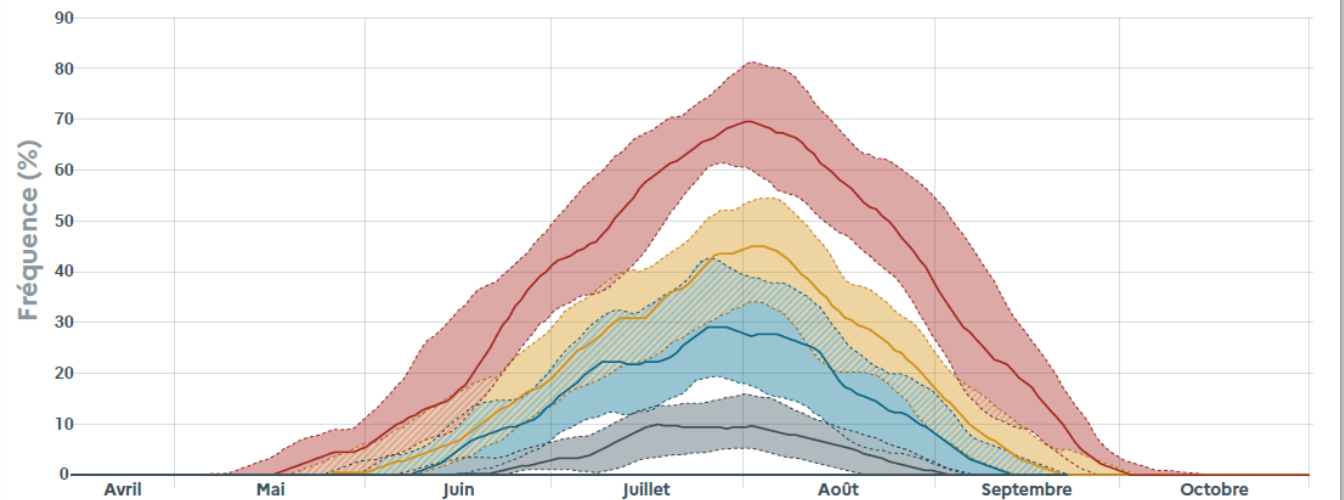
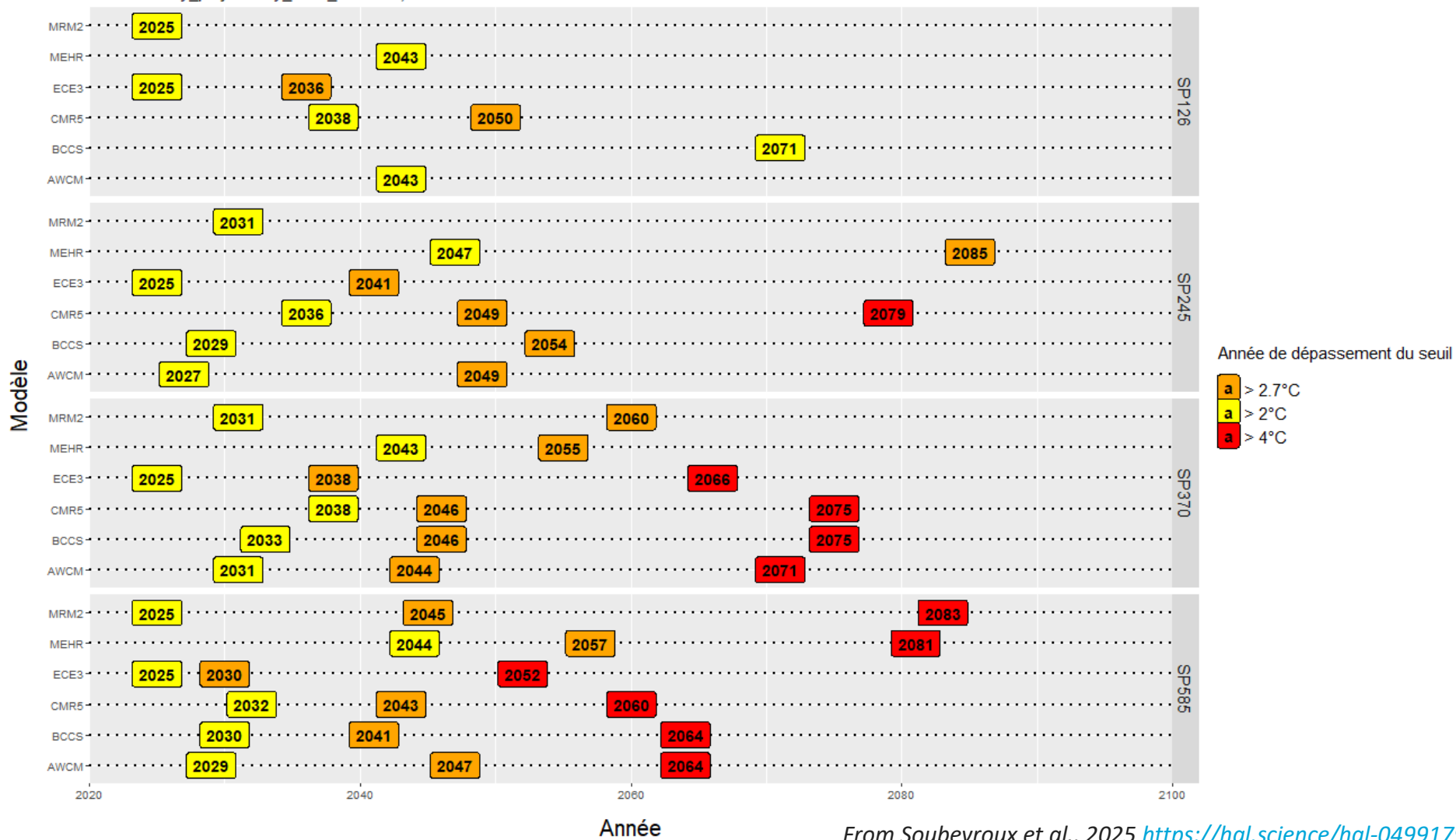


Figure 16 : Fréquence d'occurrence des vagues de chaleur à l'échelle nationale selon les différentes périodes de l'année pour la période de référence 1976–2005 et les trois niveaux de réchauffement France à +2°C (enveloppe bleue), +2,7°C (enveloppe jaune) et +4°C (enveloppe rouge), horizons TRACC 2030, 2050 et 2100, selon les quantiles 17, médiane et 83 de l'ensemble TRACC–2023.

The time of émergence of a given warming level might be critical to plan investments

Années de dépassement des seuils par modèle * scénario

$$Ecart = T_{moy_proj} - T_{moy_1976_2005} + 0,6^{\circ}C$$



Various studies conducted since 2019 have identified the hazards that pose the greatest risks to the network and its environment.

- High and widespread vulnerability
- Medium or limited vulnerability
- Low or no vulnerability

Vulnerability of existing structures

Aléas climatiques



High temperature, heatwaves



Wild fires
Caused by RTE's assets



Flooding, marine submersion



Winter storms



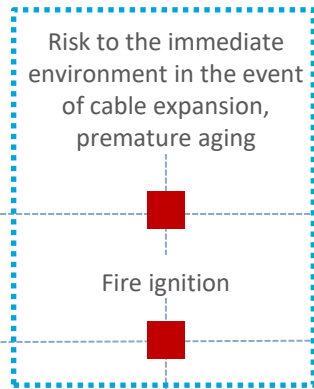
Lignes aériennes



Lignes souterraines



Postes électriques



Premature aging

Premature aging

Degradation of pylons

Long outages

Degradation of pylons and long outages*

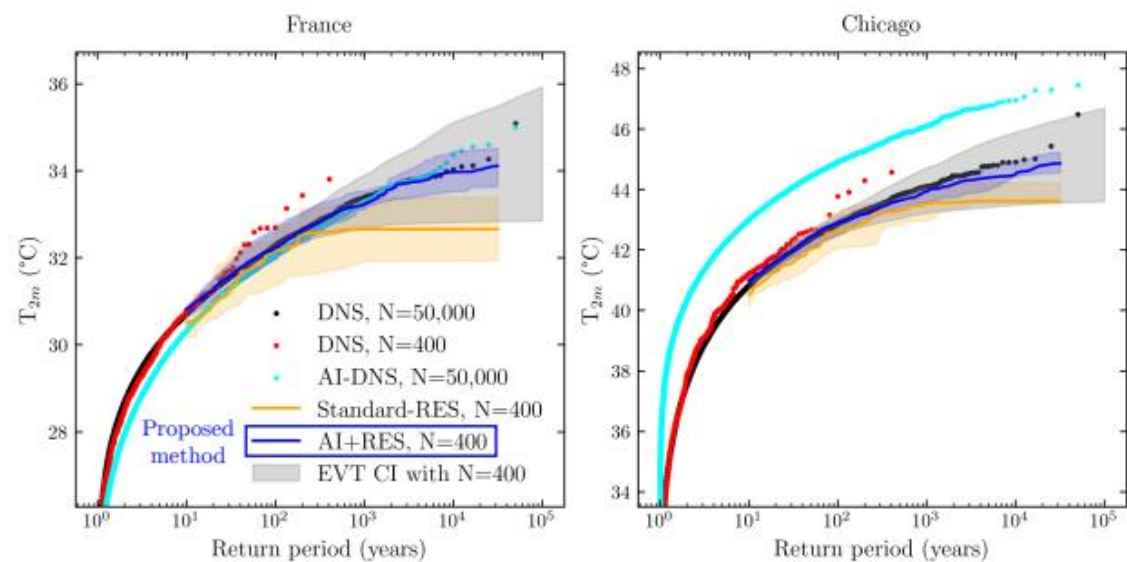
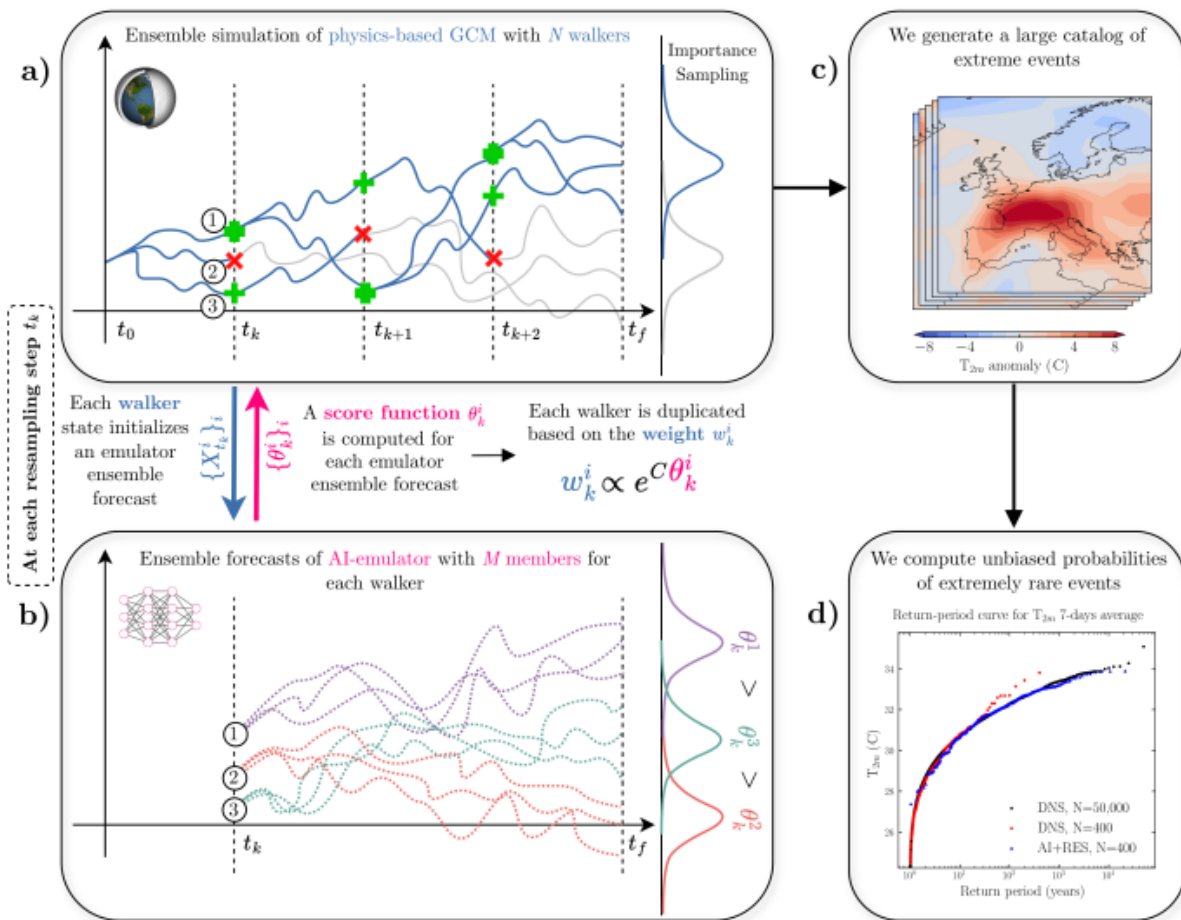
Following the vulnerability studies conducted, RTE focused on:

thermal risks (heat waves and fires) for connections,

Flooding risks for power stations and pylons

* Following the mechanical safety program, RTE's overhead network is resilient to winds of less than 180 km/h near the coast and 150 km/h inland.

EXTREMES: a promising path using AI & Rare Event Sampling



Lancelin et al., 2025 [arXiv:2510.27066](https://arxiv.org/abs/2510.27066)

Limitations & challenges regarding uncertainty assessment in energy planning

Data limitations: gaps in data availability and quality (climate but also – mainly – on the application side). Some climate data are missing (RH, wind gusts...) or the associated uncertainty is too large. Climate model improvement is still extremely necessary (resolution, processes...). Uncertainty quantification and understanding still very important.

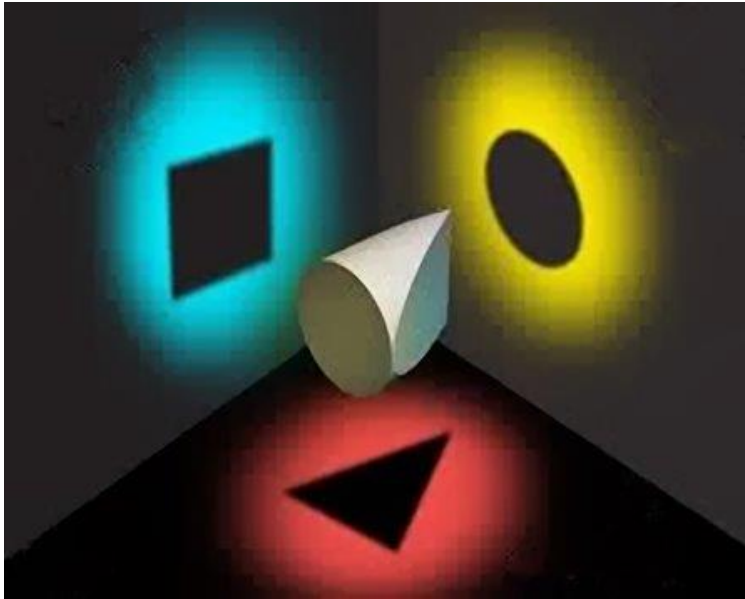
Models complexity: difficulties in integrating multiple models, data sources, and reconciling uncertainty sources

Policy and regulatory barriers: obstacles in implementing uncertainty-aware strategies

Future research: areas needing further exploration, such as advanced modeling techniques and improved data collection methods

Case studies have shown that **underestimating uncertainty** can lead to **underinvestment** in system resilience, or **conversely, costly over-engineering**.





Uncertainties are multi-faceted

❖ Role of Uncertainty

Uncertainty is a key factor in energy planning and must be addressed to ensure **system robustness and resilience**.

❖ Integrated Approaches

Bridging climate science with energy system modeling enables **adaptive strategies** for future planning. But the longer the modeling chain, the larger accumulation of uncertainties.

❖ Collaboration Importance

Collaboration among researchers, planners, and decision-makers is critical.

❖ Future Directions

Future efforts should enhance **data/uncertainty integration, modeling techniques**, and **interdisciplinary communication**

Thank you

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