ETH zürich

RRE Reliability & Risk Engineering

epse ENERGY & PROCESS SYSTEMS ENGINEERING

Multi-year storage or import dependency? - How to guarantee energy security under climate uncertainty

Leonard Göke, Stefano Moret, André Bardow

ENERDAY 2025 - Shaping Markets, Shaping Futures

Heterogenous weather risks for future energy systems
Large range of time-scales for climate impacts

System adequacy

Cuba

Cuba hit by second nationwide blackout as Hurricane Rafael makes landfall

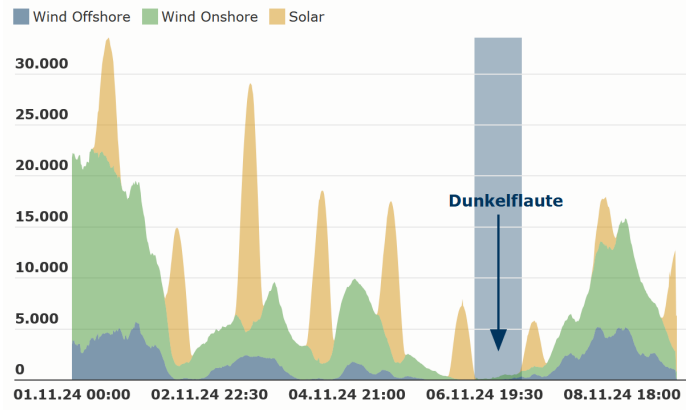
The Guardian, 06.11.2024

CALIFORNIA WILDFIRES

Wildfires hit California and Nevada, prompting evacuations and power outages

NBC News, 10.09.2024

Prolonged 'Dunkelflaute' shrinks Germany's renewables output in early November



Clean Energy Wire, 11.11.2024

Reuters

Ecuador cuts power in half of its provinces amid historic drought

Reuters, 22.09.2024

Climate change

Latin America's hydro power bet suffers effects of climate change

Financial Times, 11.11.2024

minutes | hours | days | months | decades

singular and abrupt — **compounding and gradual**

Heterogenous weather risks for future energy systems
Large range of time-scales for climate impacts

epse ENERGY & PROCESS SYSTEMS ENGINEERING
RRE Reliability & Risk Engineering

System adequacy

Cuba

Cuba hit by second nationwide blackout as Hurricane Rafael makes landfall

The Guardian, 06.11.2024

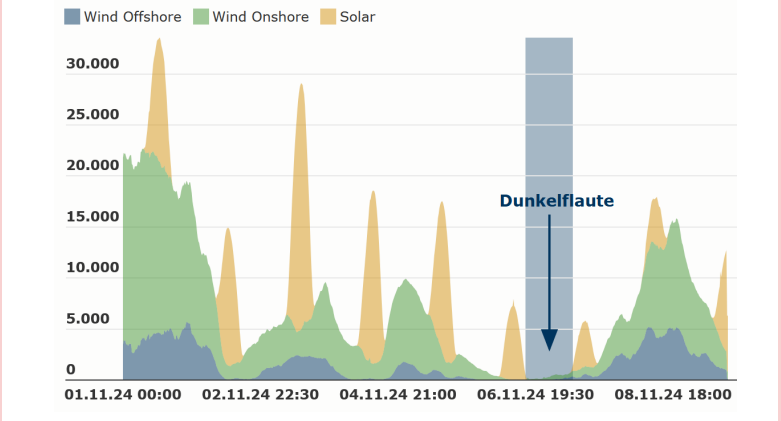
CALIFORNIA WILDFIRES

Wildfires hit California and Nevada, prompting evacuations and power outages

NBC News, 10.09.2024

Energy security

Prolonged 'Dunkelflaute' shrinks Germany's renewables output in early November



Clean Energy Wire, 11.11.2024

Reuters

Ecuador cuts power in half of its provinces amid historic drought

Reuters, 22.09.2024

Climate change

Latin America's hydro power bet suffers effects of climate change

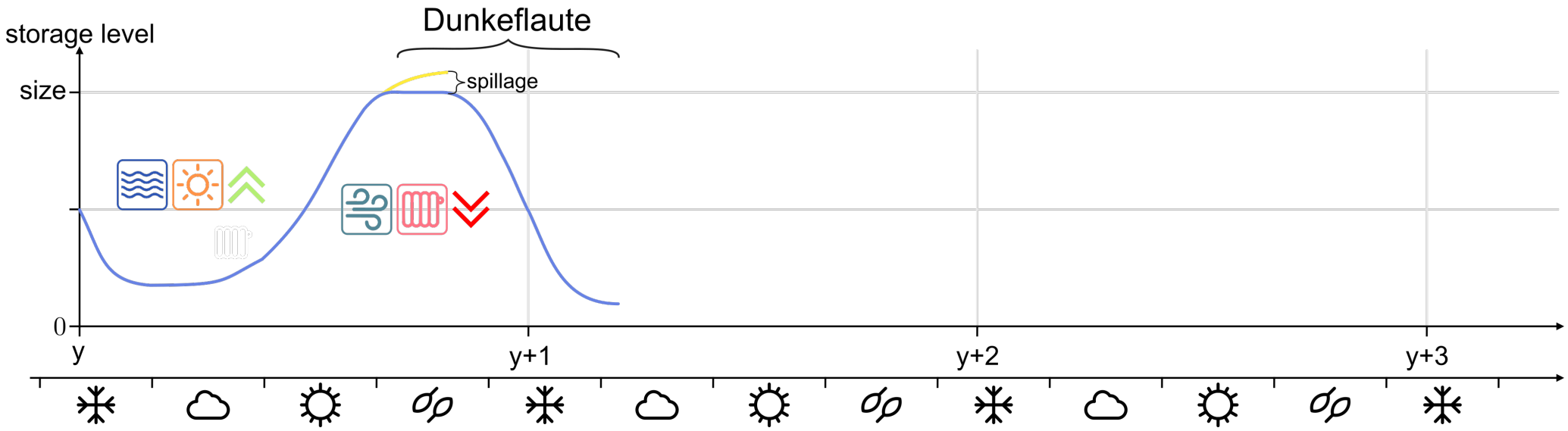
Financial Times, 11.11.2024

minutes | hours | days | months | decades

singular and abrupt — **compounding and gradual**

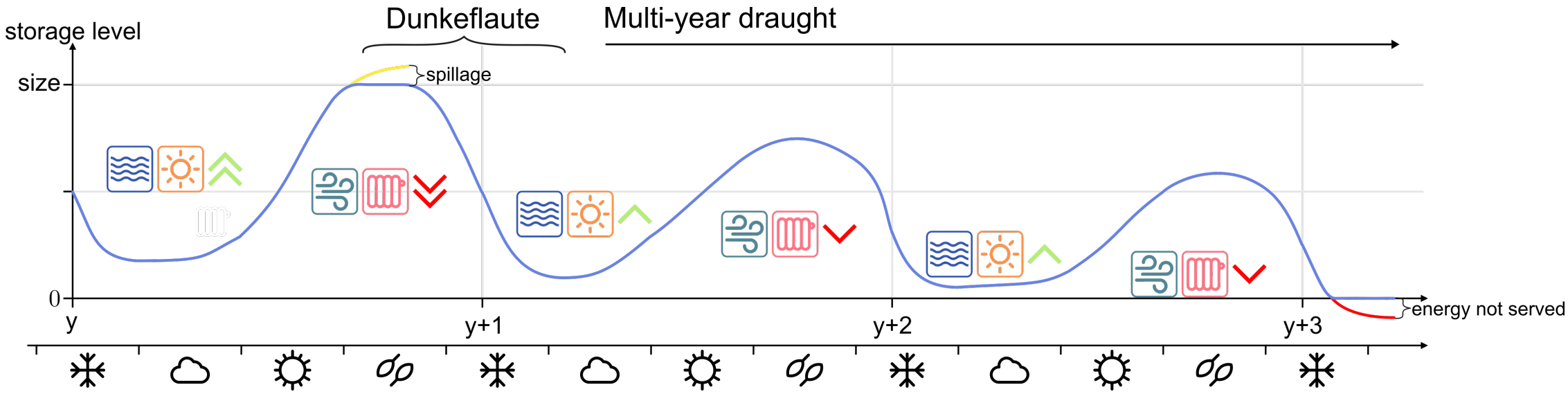
Multi-year draughts can be greater risk than Dunkelflaute

Security becomes a stochastic system problem



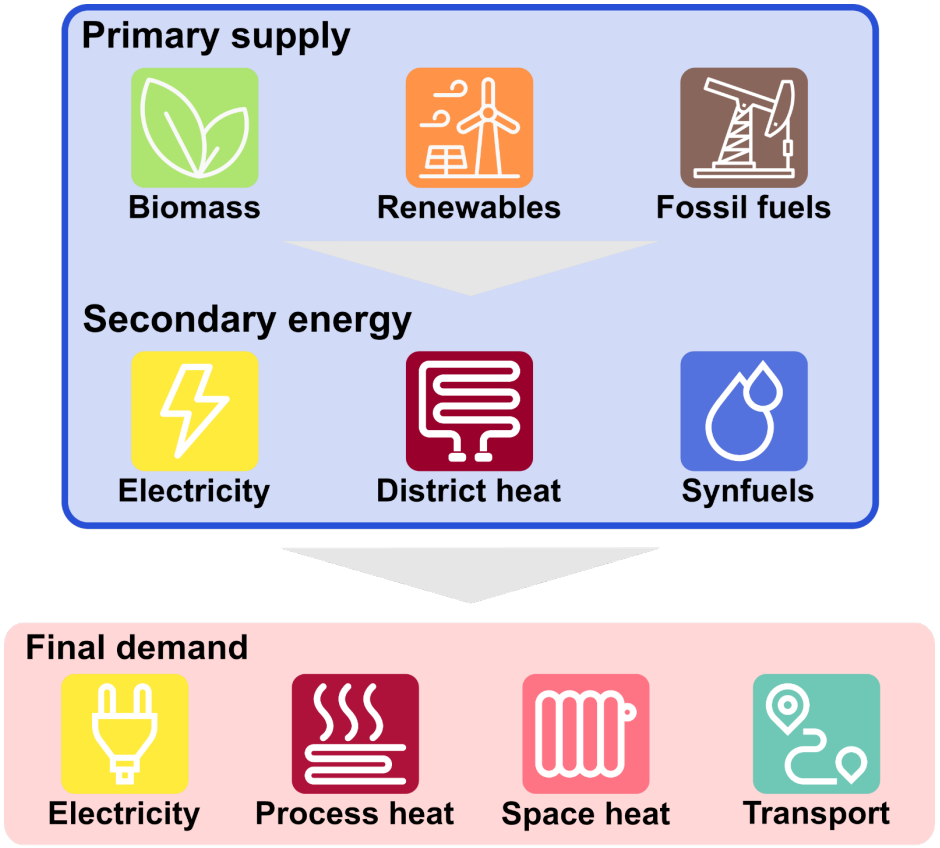
Multi-year draughts can be greater risk than Dunkelflaute

Security becomes a stochastic system problem



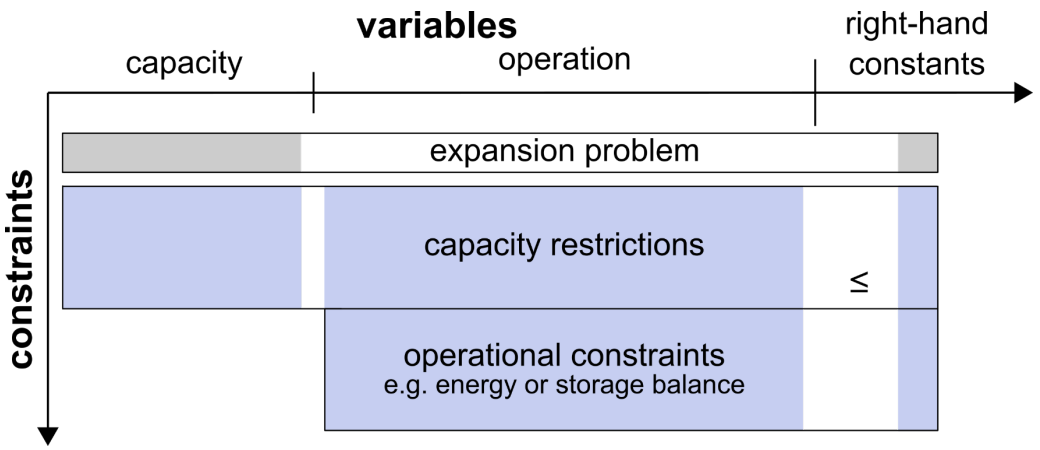
Methodology for energy system planning
Linear capacity planning of large-scale system

Sector-coupled European system [1]



Mathematical formulation [2]

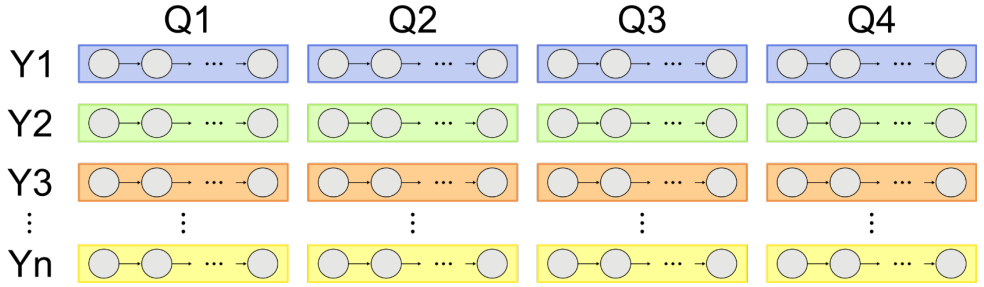
$$\begin{aligned} \min_{x,y} \quad & c^\top x + d^\top y \\ s.t. \quad & Hx \leq a \\ & Ix + Jy \leq b \\ & x \in \mathbb{R}^n_+, y \in \mathbb{R}^n_+ \end{aligned}$$



[1] Göke et al. (2023). How flexible electrification can integrate fluctuating renewables. *Energy*. 10.1016/j.energy.2023.127832.
[2] Göke (2021). AnyMOD.jl: A Julia package for creating energy system models. *SoftwareX*. 10.1016/j.softx.2021.100871.

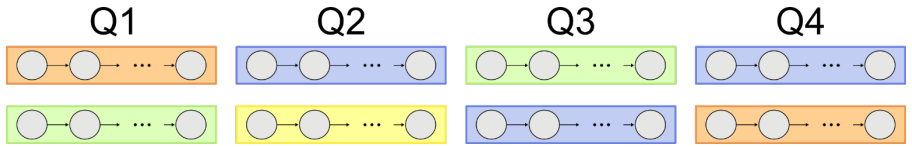
Stochastic approach to climate uncertainty
Subsampling of historic dataset

Initial dataset [3]



Assume uncorrelated quarters
→ Stochastic independence

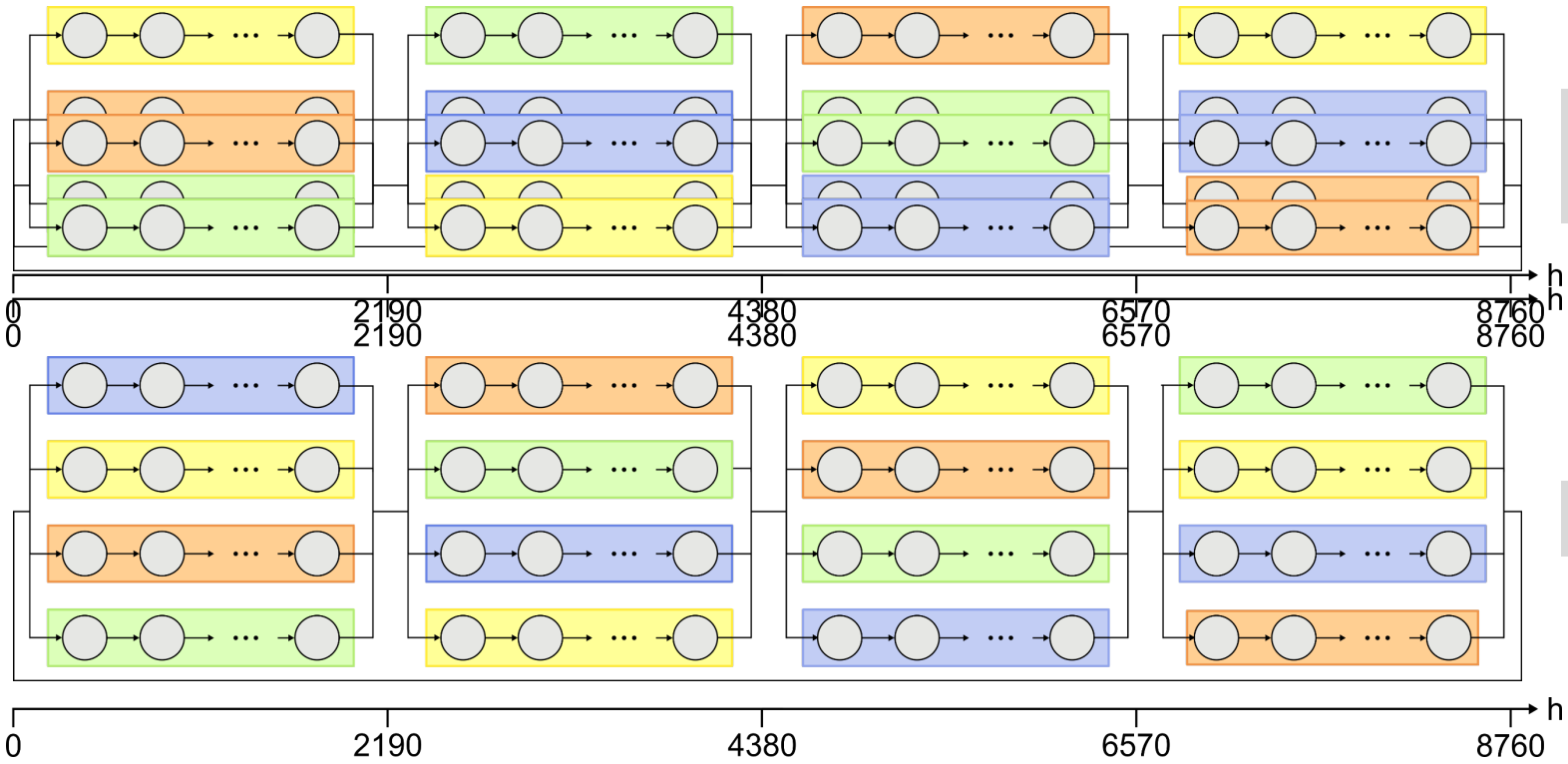
Select representative quarters



[3] ENTSO-E (2021). Pan-European Climatic Database 3.1.

Combinatorial modeling to cover numerous samples

Cover large range of events without explicit representation

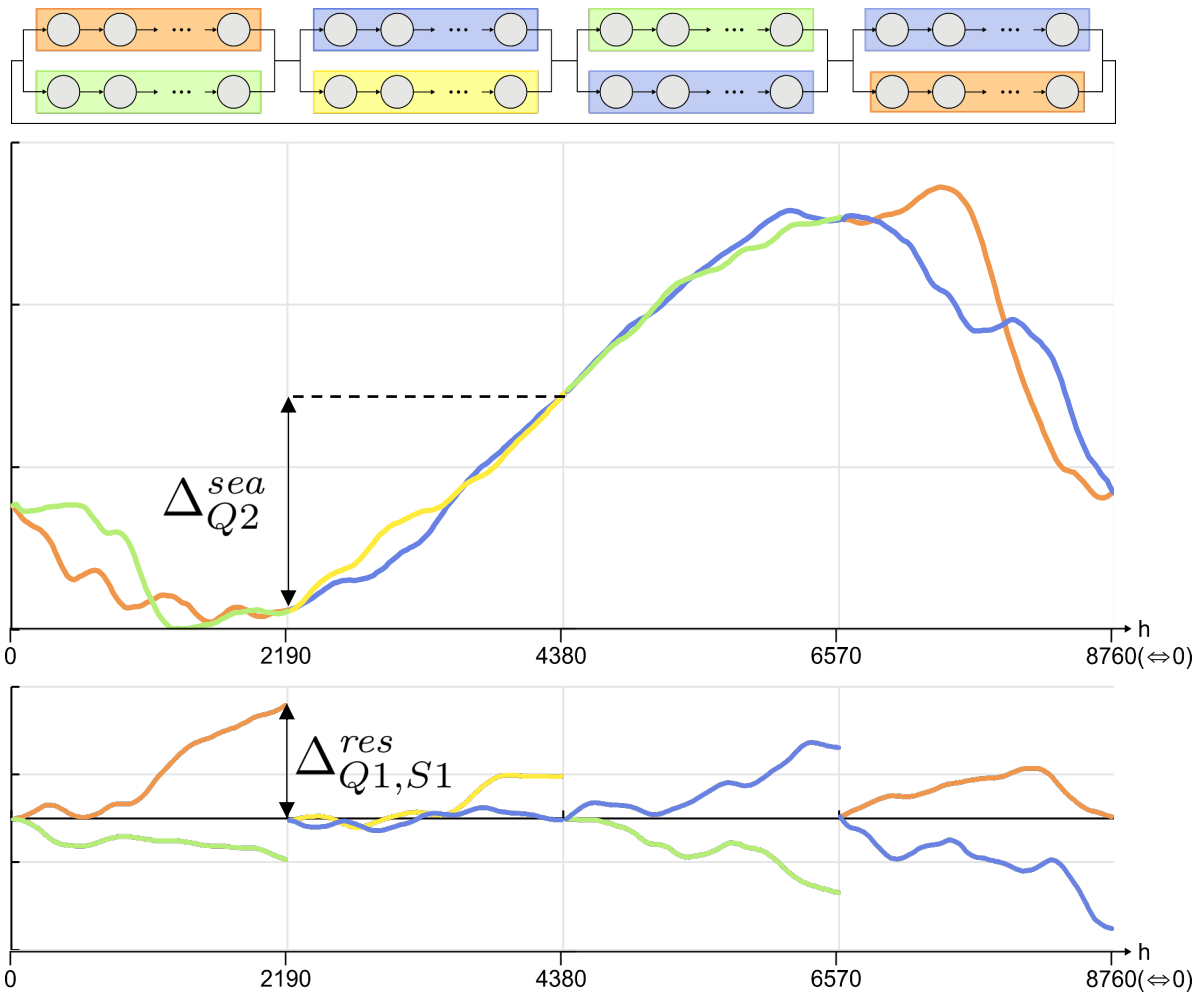


3^4 (=81) scenarios

2^4 (=16) scenarios

4^4 (=256) scenarios

Storage modeling in combinatorial setup
Seasonal component and reserve component

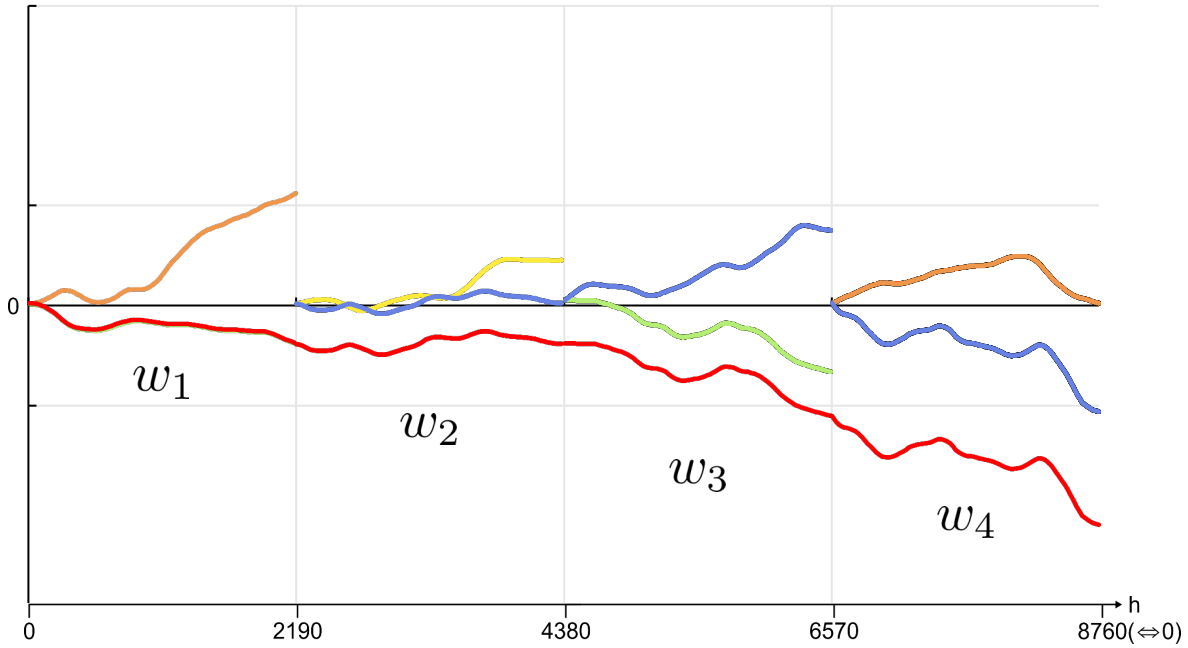


$$\underbrace{lvl_{t,s}}_{\substack{\text{storage}\\ \text{level}}} = lvl_{t-1,s} + \underbrace{in^{bal}_{t,s} - out^{bal}_{t,s}}_{\substack{\text{charge/discharge}\\ \text{to energy balance}}} + \underbrace{in^{res}_{t,s} - out^{res}_{t,s}}_{\substack{\text{charge/discharge}\\ \text{from reserve}}} \quad \forall t \in T, s \in S$$

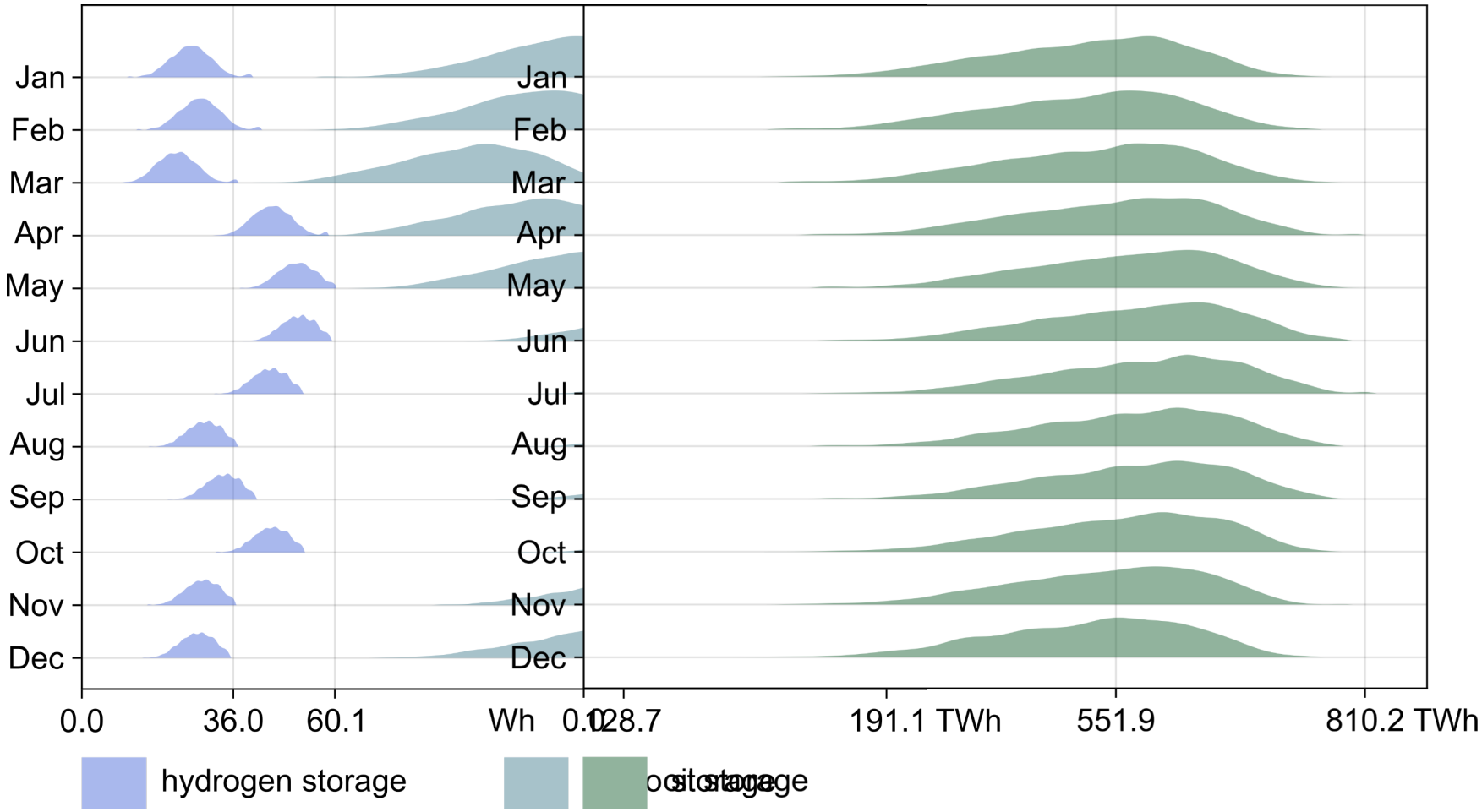
S

S

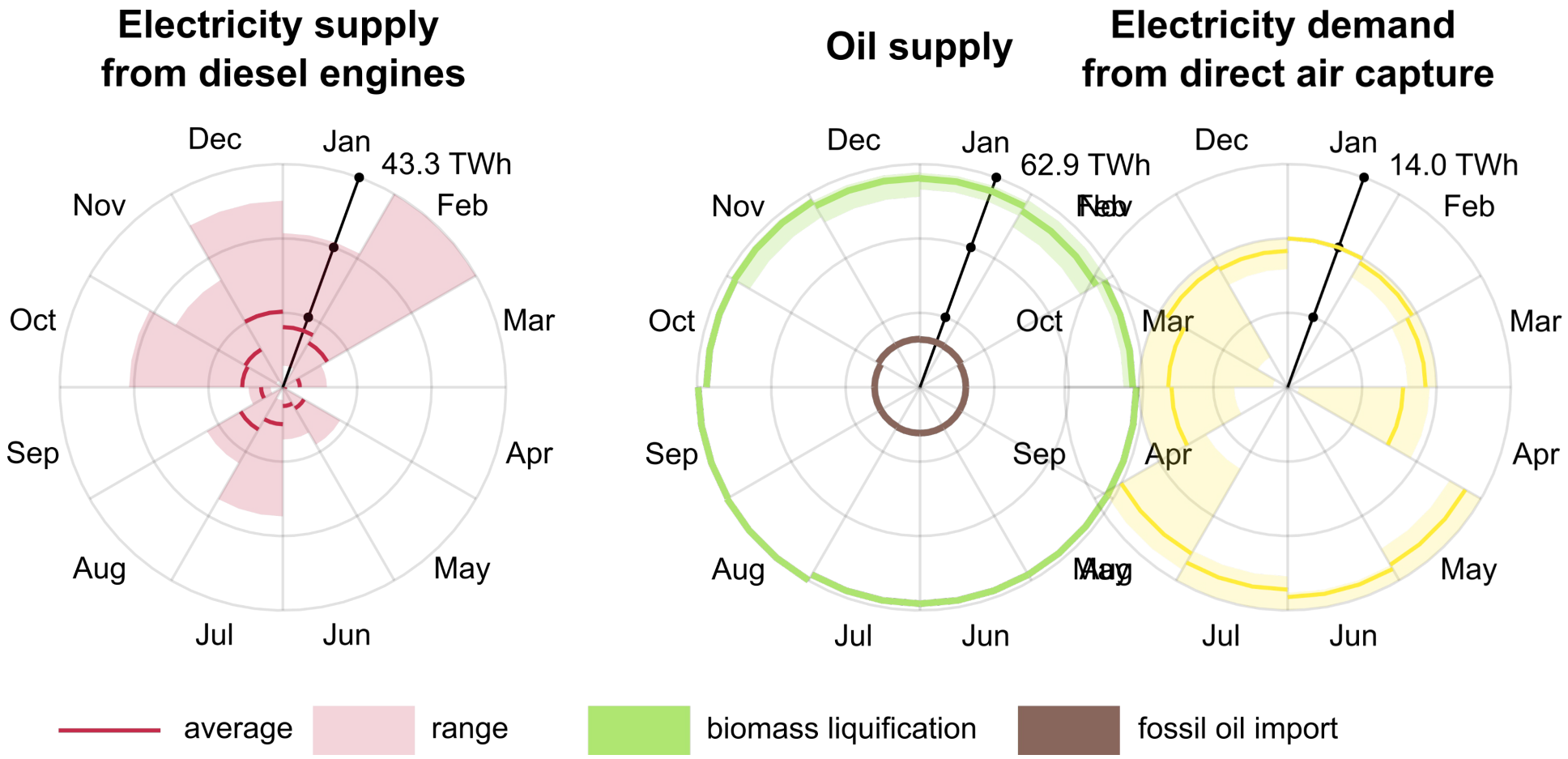
Storage modeling in combinatorial setup
Robust formulation to identify worst-case scenario



Preliminary results
Technologies for seasonal and multi-year balancing



Preliminary results
Reserve balances supply and demand for fuels across years



What is next?

Conclusions

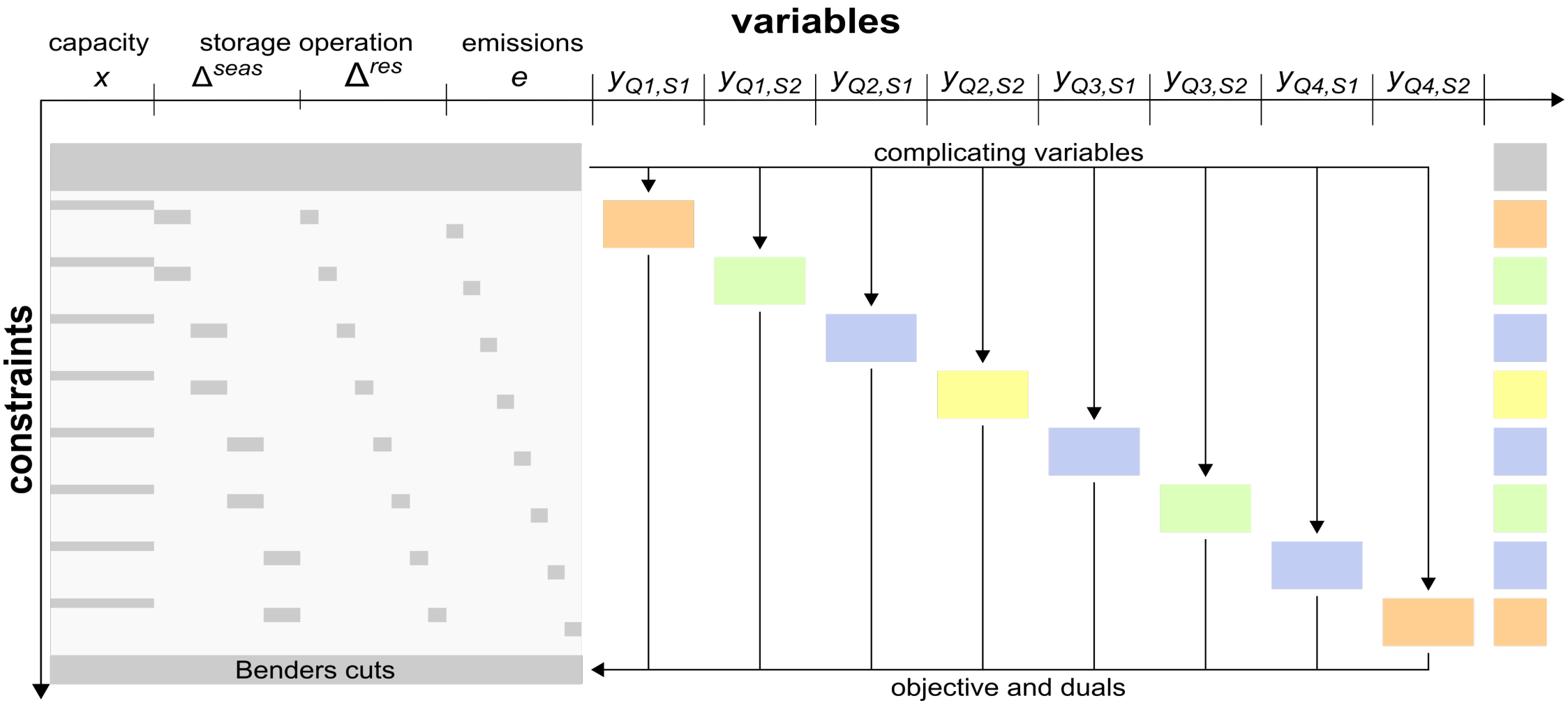
- Scalable method for stochastic planning to secure future systems against climate uncertainty
- Storage needs for resilience against multi-year draughts are substantial, but far below today's fuel reserve
- Multi-year storage decrease system costs of a resilient system by ~7%

Outlook

- Vary flexibility of synthetic and fossil imports from outside of Europe
- Reduce biomass availability for the energy system

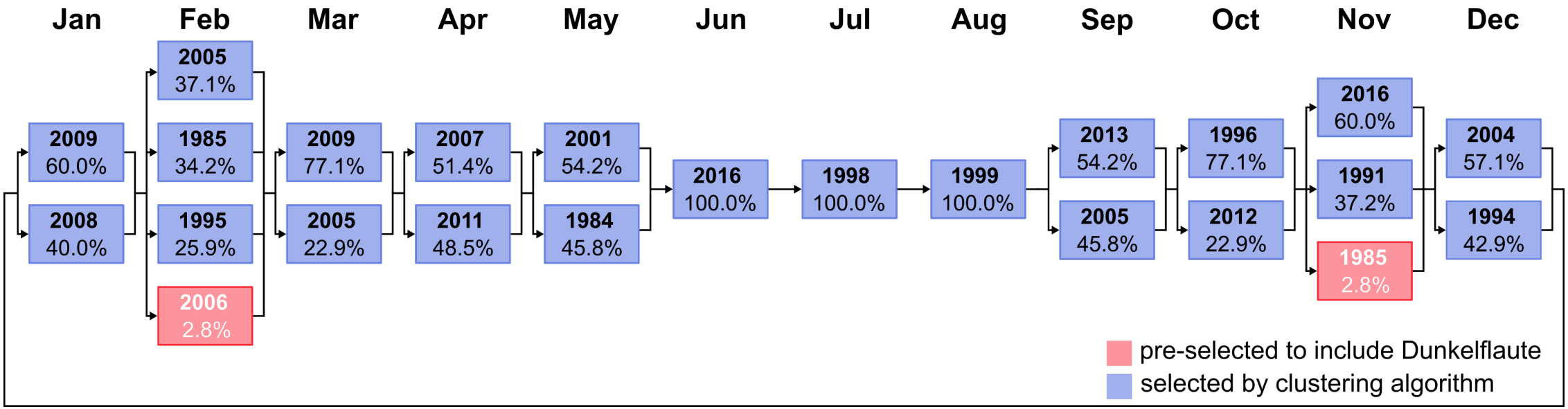
Thank you for your attention!

Benders decomposition to solve stochastic problem
Storage level and emissions add complicating variables

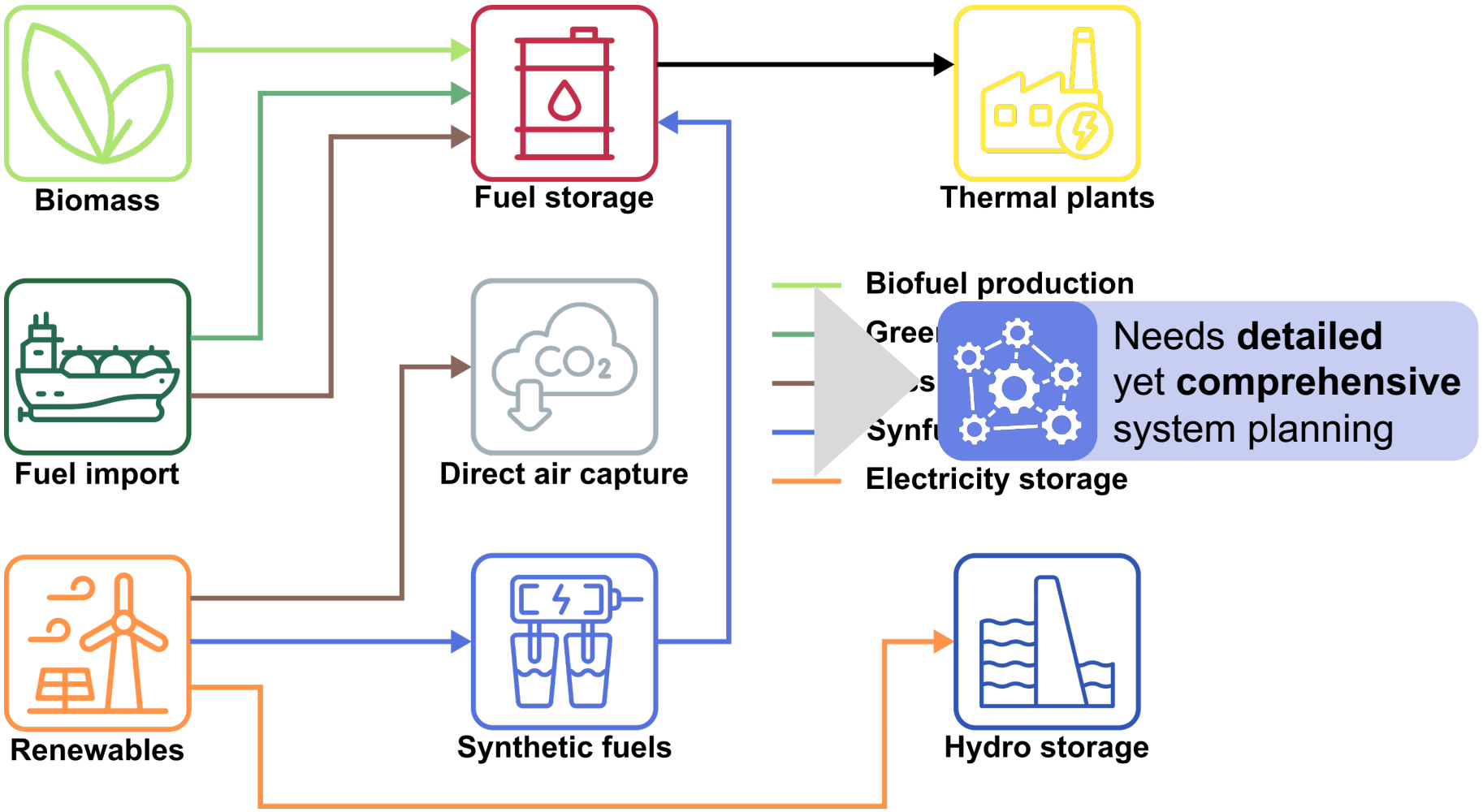


[7] Göke et al. (2024). Stabilized Benders decomposition for energy planning under climate uncertainty. *European Journal of Operational Research*. 10.1016/j.ejor.2024.01.016.

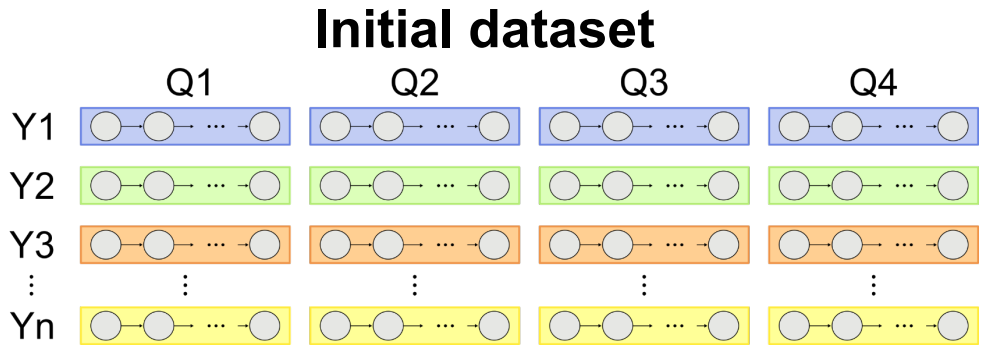
Representative months selected by optimization
Exemplary result when selecting 24 months in total



What security options must be considered?
Various complex and interdependent storage paths



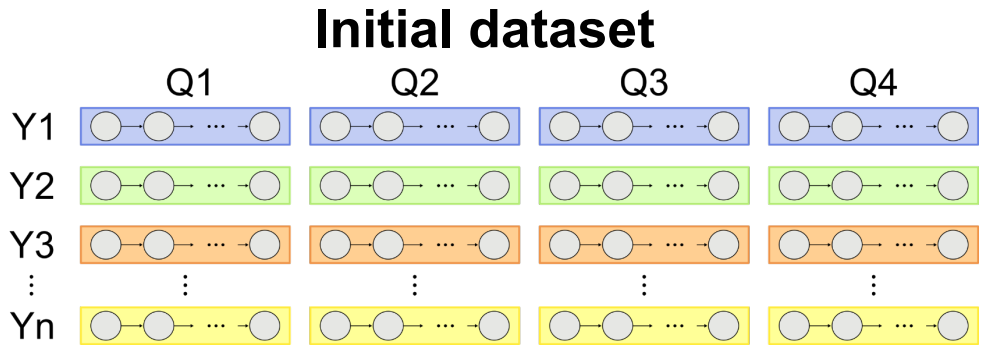
What is the status-quo to consider climate uncertainty?
Isolated analysis of individual weather years [5,6]

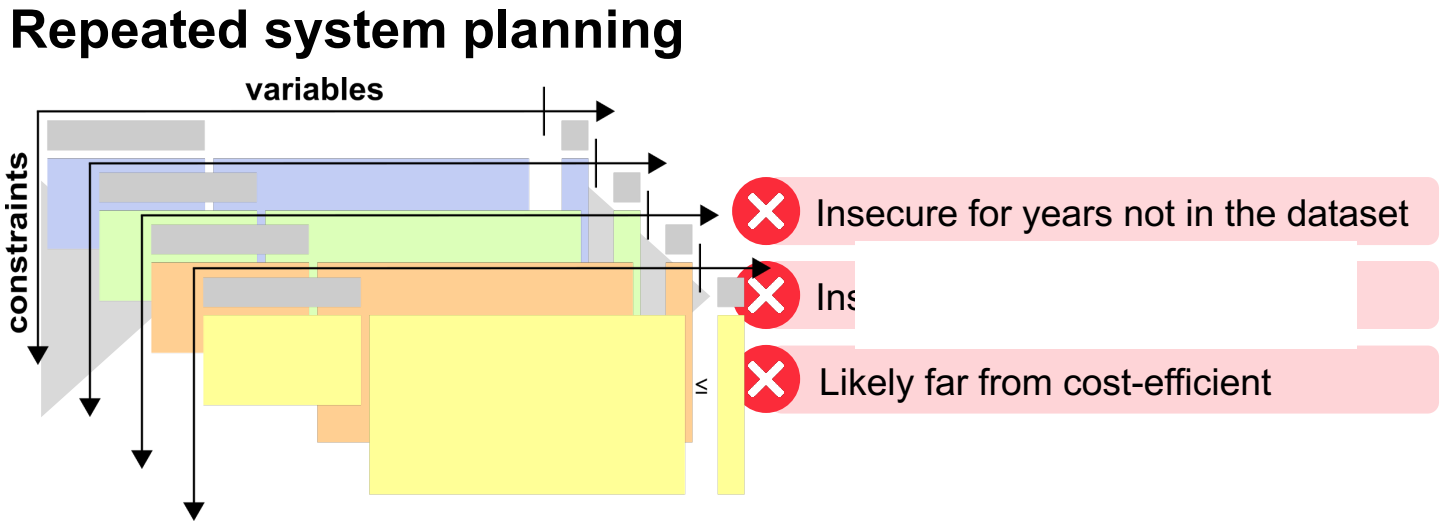


[5] Grochowicz et al. (2024). Using power system modelling outputs to identify weather-induced extreme. *Environmental Research Letters*. 10.1088/1748-9326/ad374a.
[6] Gøtske et al. (2024). Designing a sector-coupled European energy system robust to 60 years of historical weather data. 10.48550/arXiv.2404.12178.

What is the status-quo to consider climate uncertainty?

Isolated analysis of individual weather years [5,6]





[5] Grochowicz et al. (2024). Using power system modelling outputs to identify weather-induced extreme. *Environmental Research Letters*. 10.1088/1748-9326/ad374a.

[6] Gøtske et al. (2024). Designing a sector-coupled European energy system robust to 60 years of historical weather data. 10.48550/arXiv.2404.12178.