Empa
Materials Science and Technology

Wind Energy in Switzerland: Shaping Future Energy System with Robust Planning Frameworks

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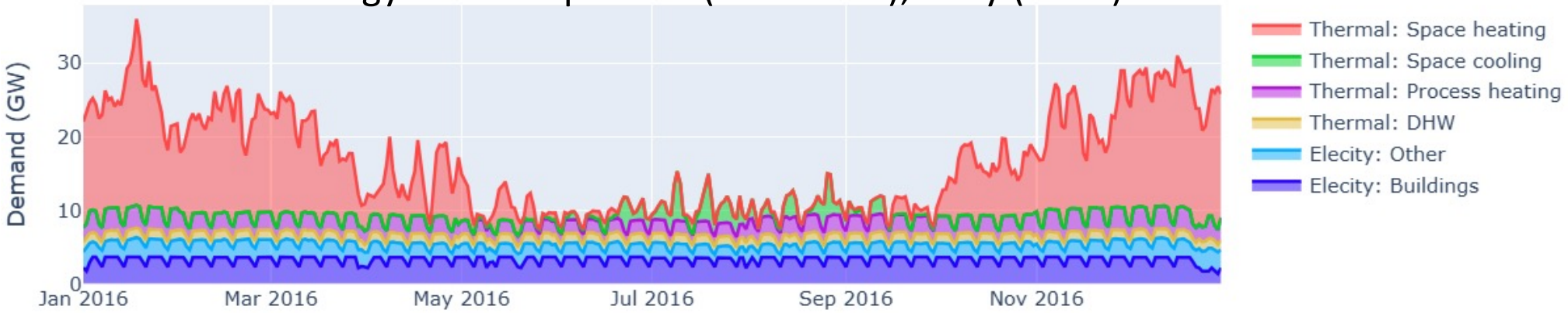
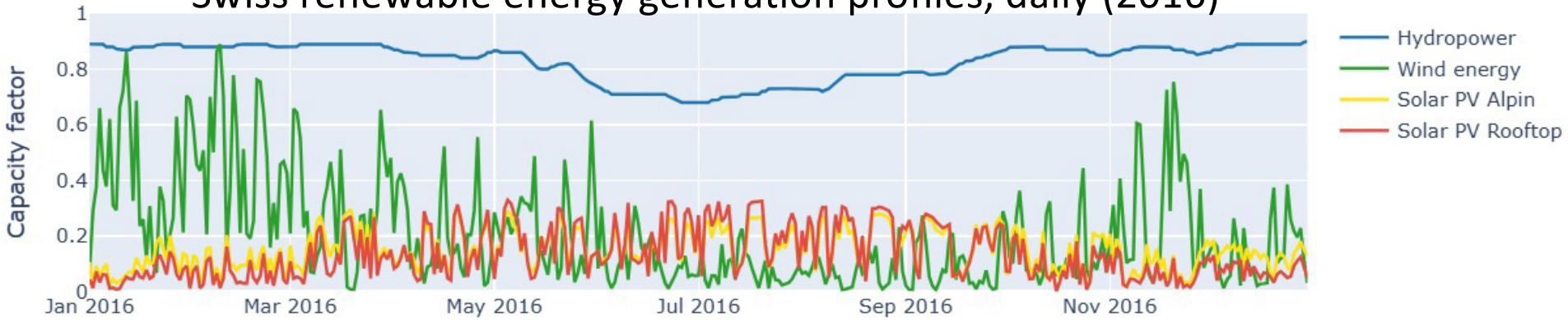
Motivation: Why Wind in Switzerland

Swiss energy demand profiles (estimated), daily (2016)



Swiss renewable energy generation profiles, daily (2016)



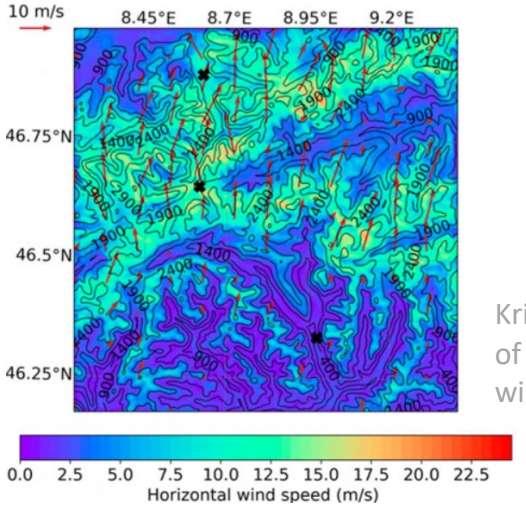
Energy Strategy 2050 target: 4.3 TWh/a in 2050 (7% of electricity supply)
…Today: 0.2 TWh/a in 2025 (0.3% of electricity supply)

Key Barriers Today

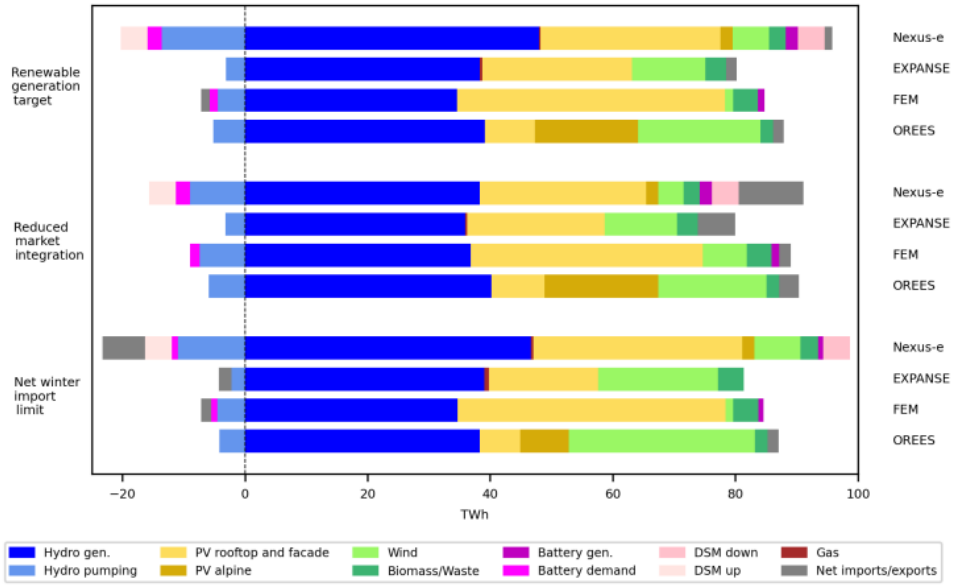
- Social and Community Acceptance
  - Landscape and Aesthetic Concerns
  - Wildlife and Ecology
  - Health and Annoyance
- Geographical and Technical Complexity
  - Alpine Mapping Difficulties
  - Infrastructure and Costs
  - Prohibited Zones
- Administrative and Regulatory Hurdles
  - Lengthy Planning Horizons
  - Decentralised Governance
  - Legal Challenges

State of the Art & Research Gap

- State of the Art
  - Wind resources assessment: Several studies have assessed wind resources in Switzerland using high spatial resolution data (e.g. ML, topography, Alpine flows)
  - Wind power in the energy system: Several national energy system modelling studies include wind energy, but simplify wind data and lack the spatial granularity to inform regional-level planning.

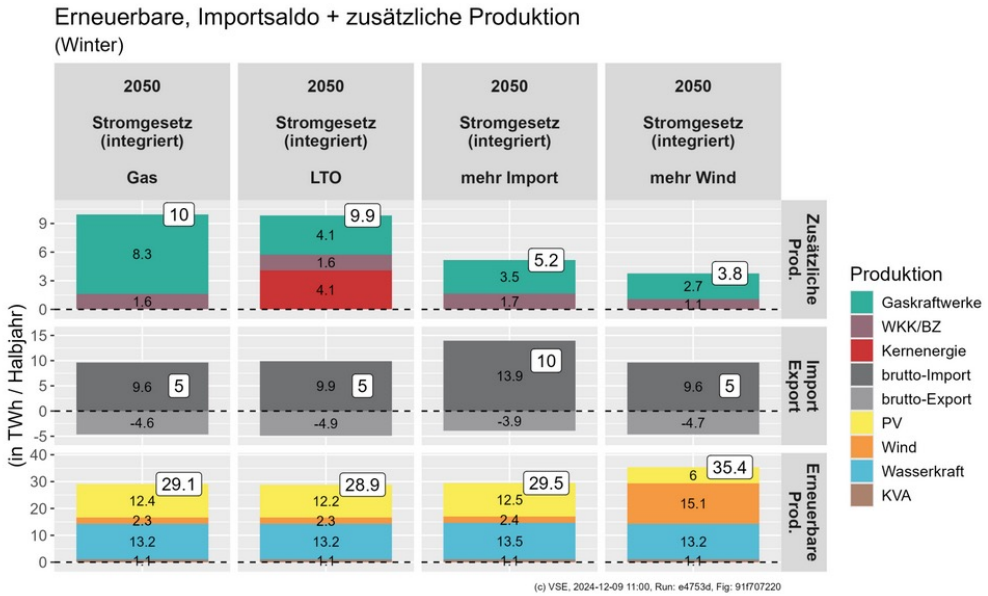


Kristianti et al. (2024). Influence of air flow features on alpine wind energy potential.



ETH Zürich (2025). Renewable Energy Outlook II for Switzerland.

ehubX/SwissX (Swiss Energy System Model)



Zusammenfassung der erneuerbaren und ergänzenden (zusätzlichen) Produktion sowie des Importsaldos zur Deckung des Landesstromverbrauchs für das Szenario «Stromgesetz mit Stromabkommen» und den vier untersuchten Varianten «Gas», «LTO», «mehr Import» und «mehr Wind».

National analysis:

sweet swiss energy research for the energy transition
reFuel.ch

Regional analysis:

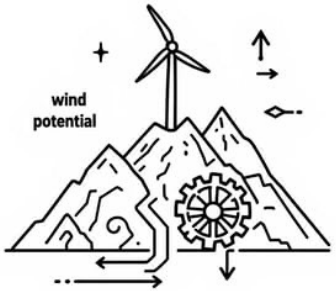
Rheintal, DigiSisslerfeld…

Research gap:

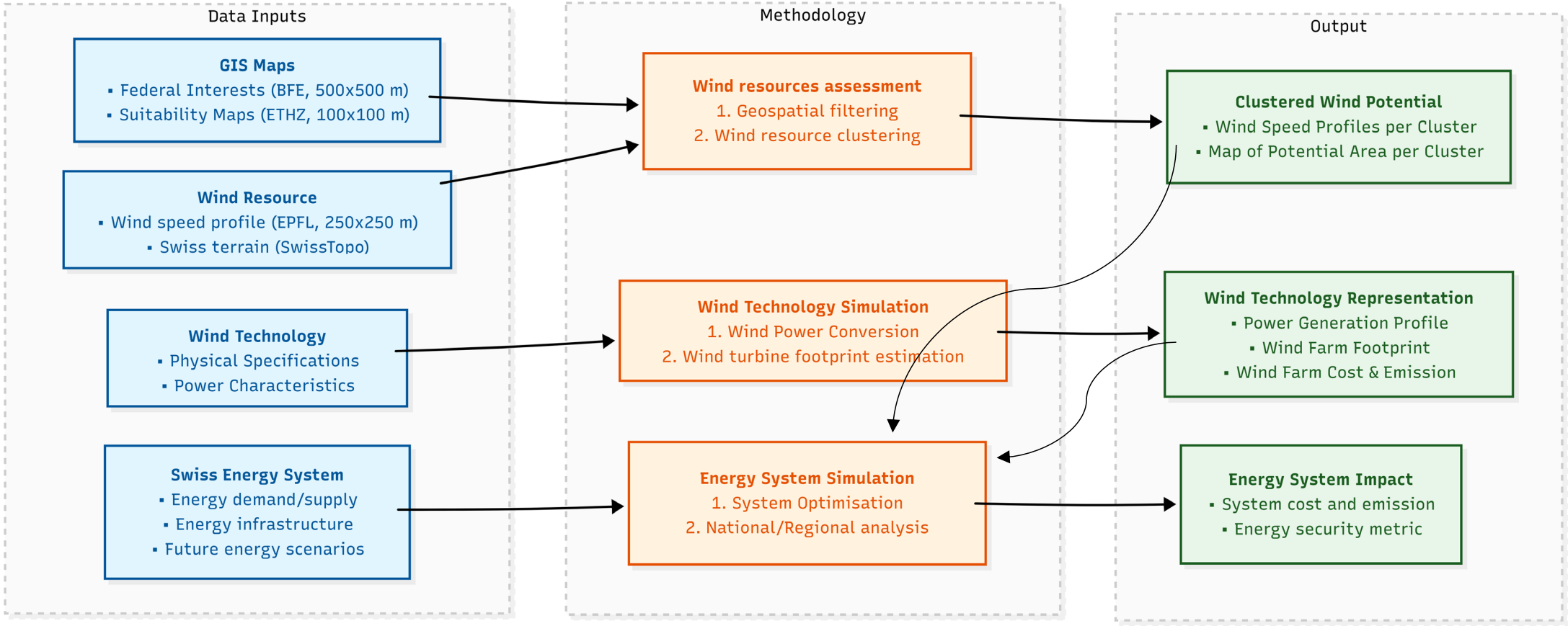
Lack of System-Oriented Assessment of Wind Deployment Strategies with high-resolution wind considering

Research Objectives

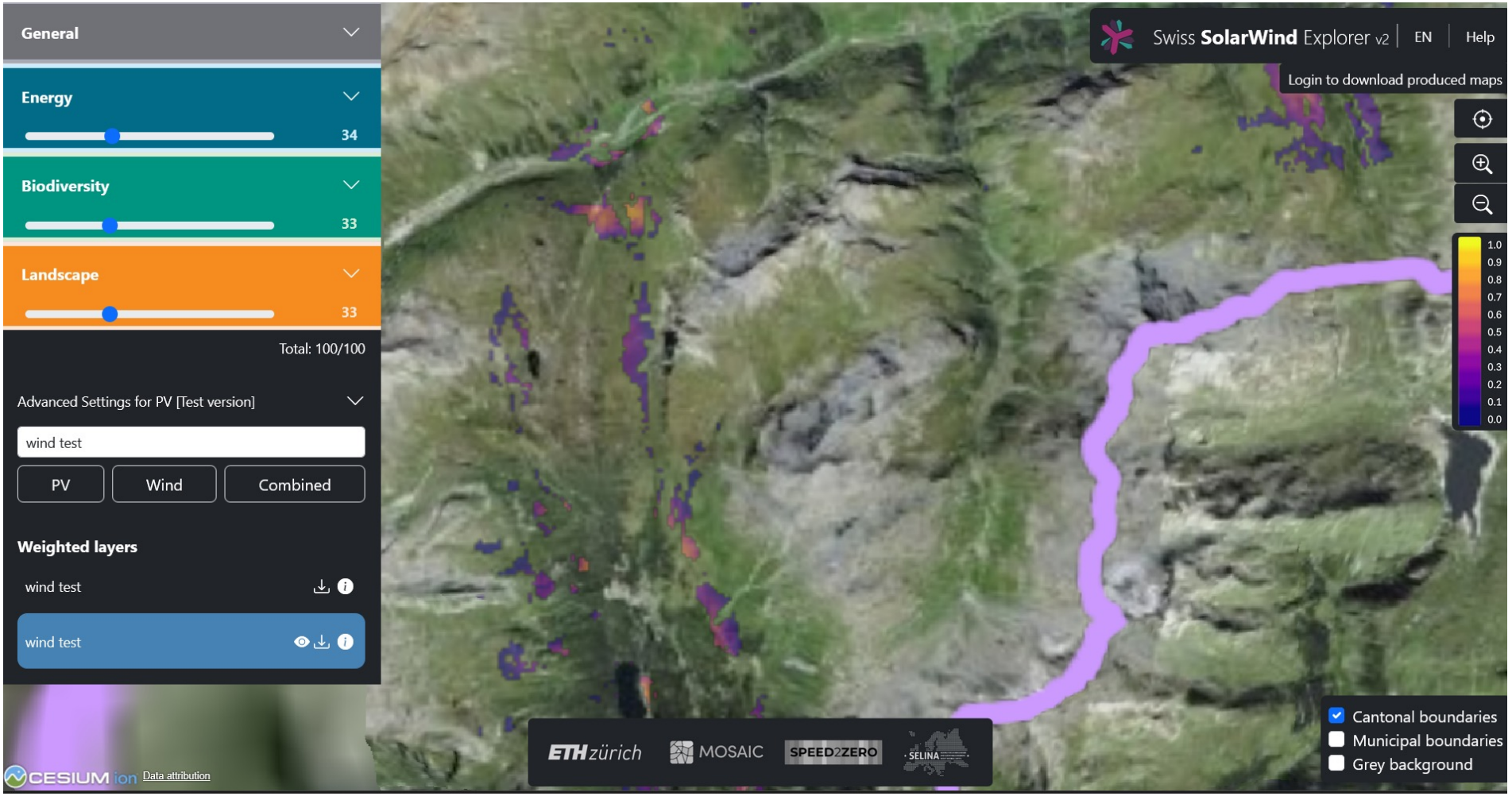
- Developing the wind energy assessment framework considering:
  - **Geospatial Constraints:** Addressing landscape, wildlife, and proximity to residential areas to ensure ecological and social compatibility.
  - **Geographical and Technical Parameters:** Navigating complex terrain, infrastructure limitations, and regulatory restrictions in alpine and urban environments.
  - **Energy System Transition and Climate Targets:** Aligning wind energy development with regional and national climate goals, then support the decisionmaking process.



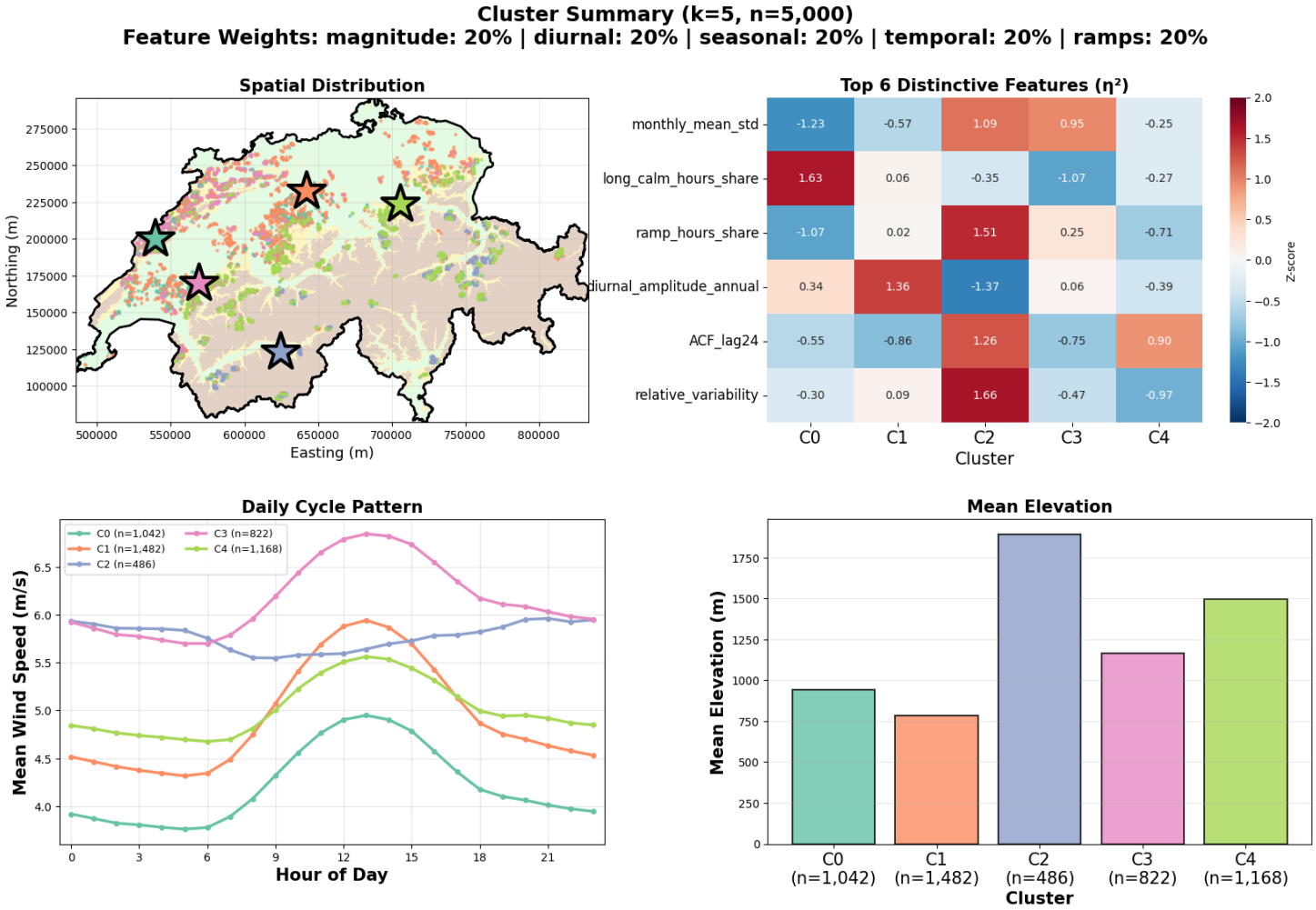
Overall Modelling Framework



Swiss SolarWind Explorer (ETH Zürich, SPEED2ZERO)



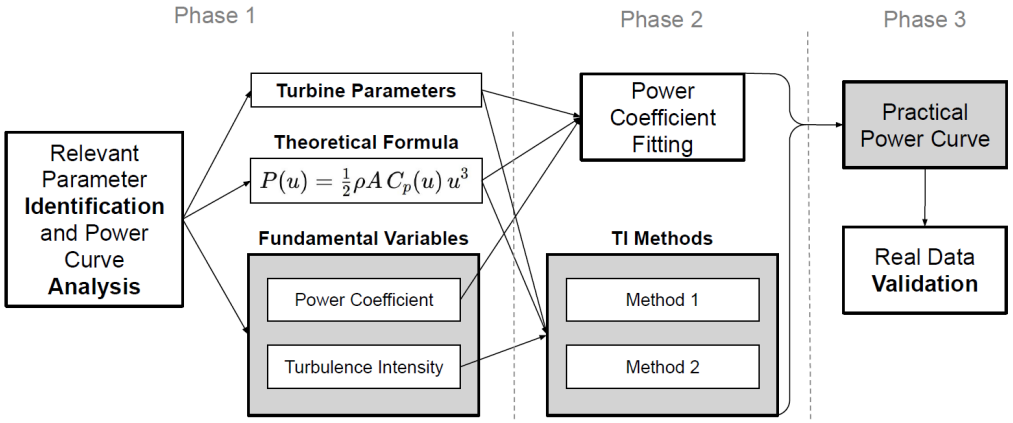
1. Wind Profile Clustering and Representation



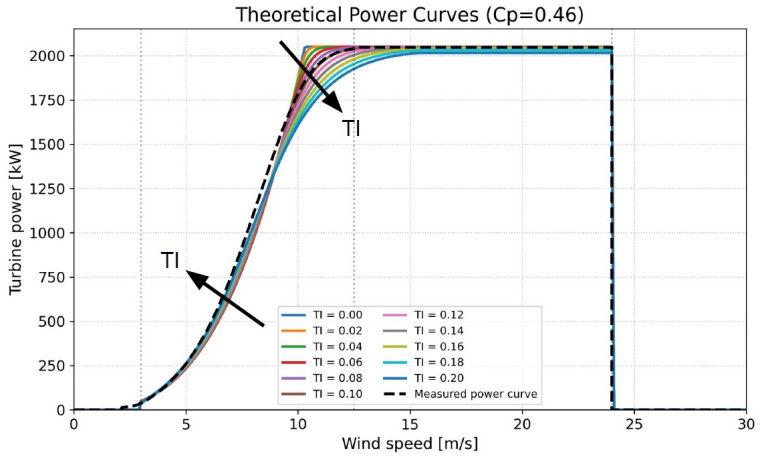
- The wind potential areas are clustered based on wind resources and geographical features.
- Number of clusters, weighting for geospatial filtering, and feature clustering can be customised.
- The cluster profiles and potential area are feed into energy system modelling.

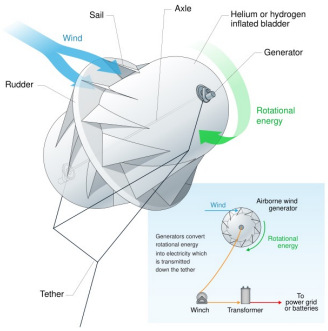
Source: Elena Buchinger, 2026, Clustering Approaches to Derive Representative Wind Profiles for Energy System Modelling in Switzerland

2. Wind Turbine Technology Modelling



- **Wind Power Generation Modelling:**
  - Based on **general turbine characteristics** or **power curve** for performance estimation.
  - **Hub height** (critical for wind speed calculation).
  - **Wind turbine footprint per capacity** (defines spatial and land-use requirements).
- **Key Features: Flexible modelling inputs** enable simulation of diverse wind turbine types, supporting adaptable and scalable energy system analysis.



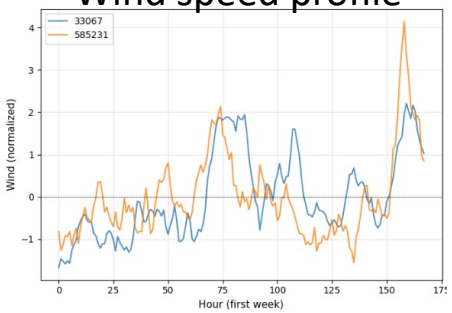


Source: Laurenz Ebi, 2026, Design and Integration of an Enhanced Wind Module for Energy System Optimization

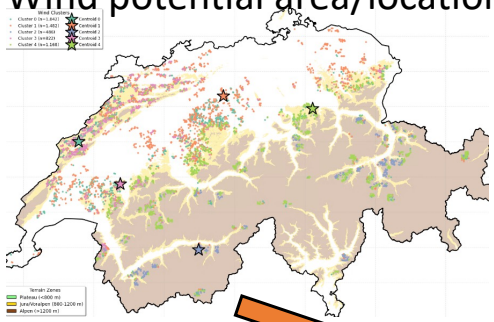
Source: Wikimedia Commons

3. Energy System Integration (ehubX)

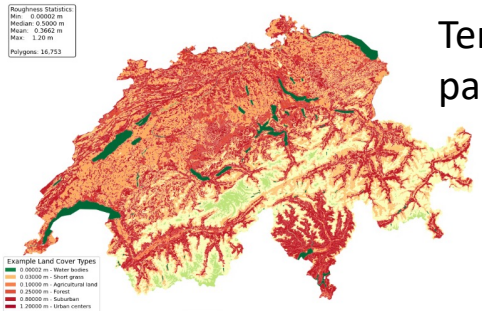
Wind speed profile



Wind potential area/location



Wind technology



Terrain-specific parameter

Swiss Energy System Model
(Multi-sectors, stages, and scenarios)

National analysis
(how could the wind turbines distribute?)

Regional analysis
(where to install wind turbines? What type of wind turbines?)

Outlook & Limitations

- Outlook:
  - This framework can be the tool to provide insights for wind energy planning at national and regional levels, by integrating geospatial constraints, high-resolution wind resources, various wind technologies, and the integration with the energy system.

- Limitations:
  - The number of clusters has a significant impact on the computational cost of the energy system model
  - The wind data (EPFL, 2022) not able to capture all the dynamic of wind speed variations.
  - Wind farm planning and site selection are no taken into account, especially the uncertainty in the developing phase.

Adaptive Planning for Wind Energy Site Selection

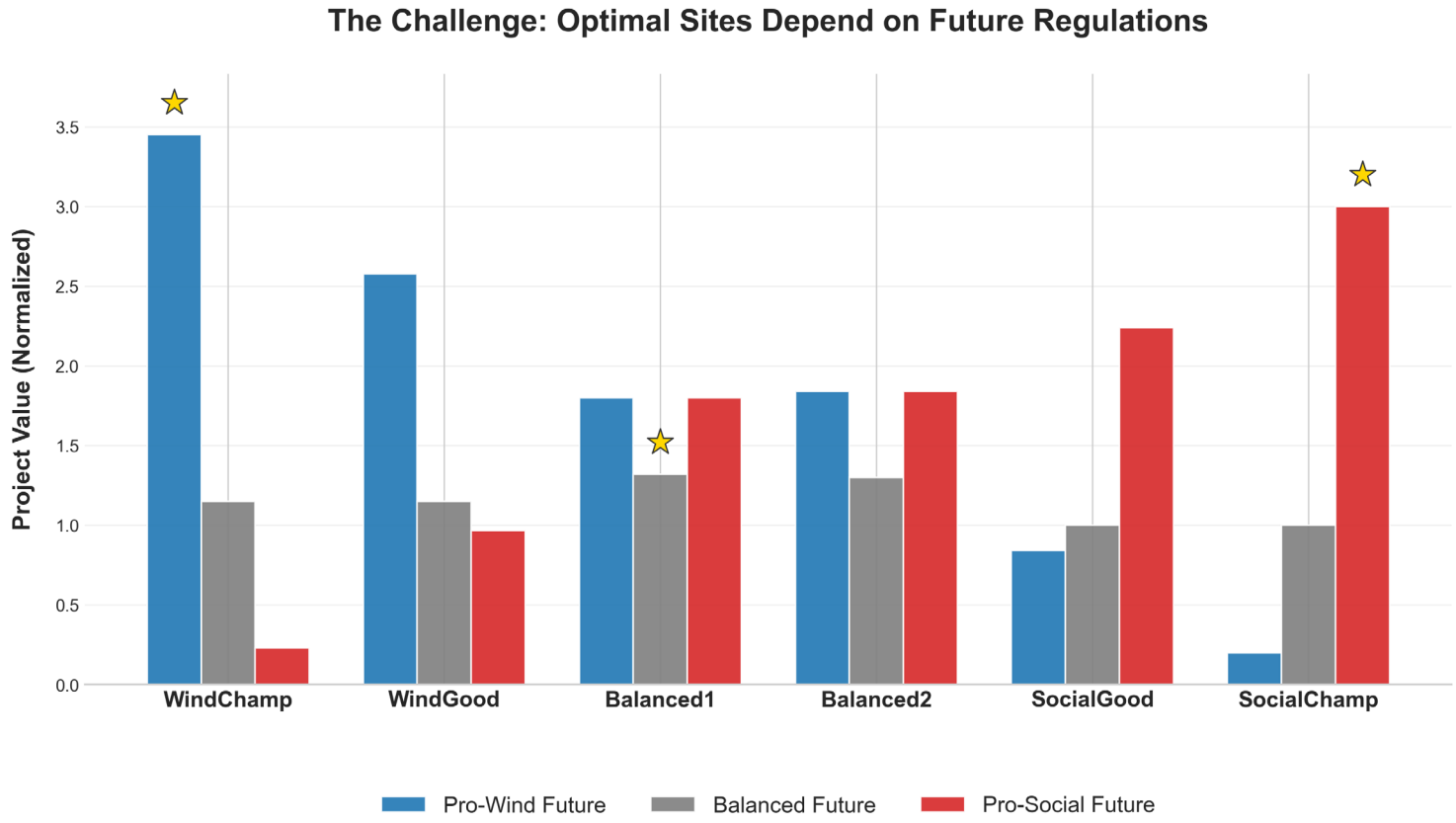
Quantifying the Option Value of Sequential Decision-Making Under Uncertainty

Model Specification & Assumptions

- Time Horizon: 3 discrete decision periods (t=0, 1, 2)
- Uncertainty: 3 distinct regulatory scenarios (Pro-Wind, Balanced, Pro-Social)
- Learning Process: Bayesian updates via noisy Gaussian signals ($\sigma = 0.2$)
- Objective Function: Maximize posterior Expected Value (EV) at each step
- Realism: Switching costs (0.1) and hysteresis to prevent noisy pivoting

The Decision Problem: Structural Uncertainty

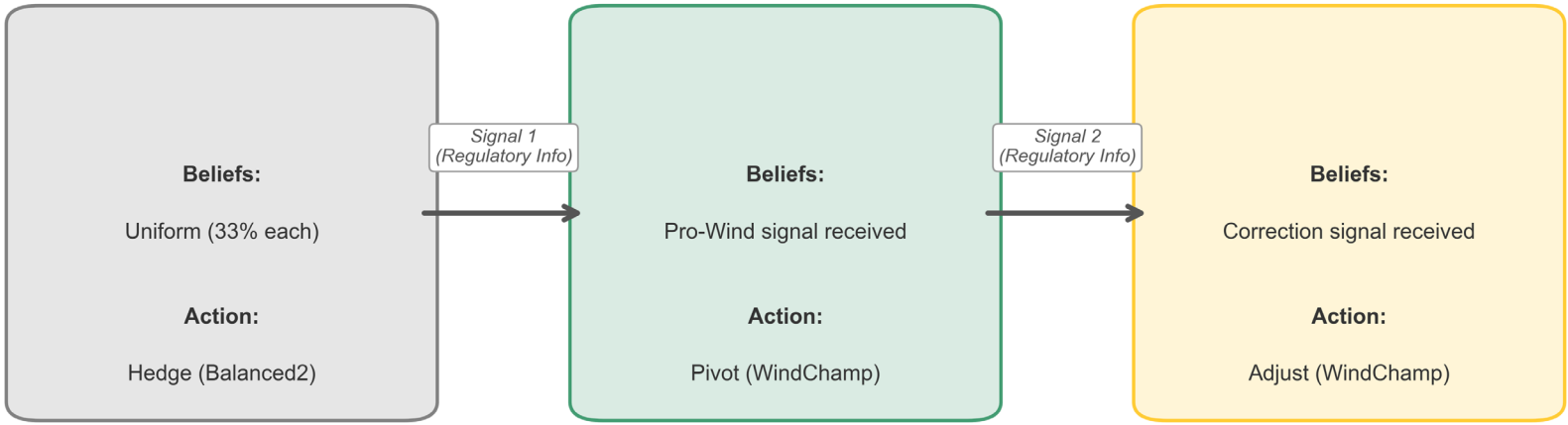
Optimal portfolio composition is highly sensitive to regulatory outcomes



Methodology: Bayesian Adaptive Framework

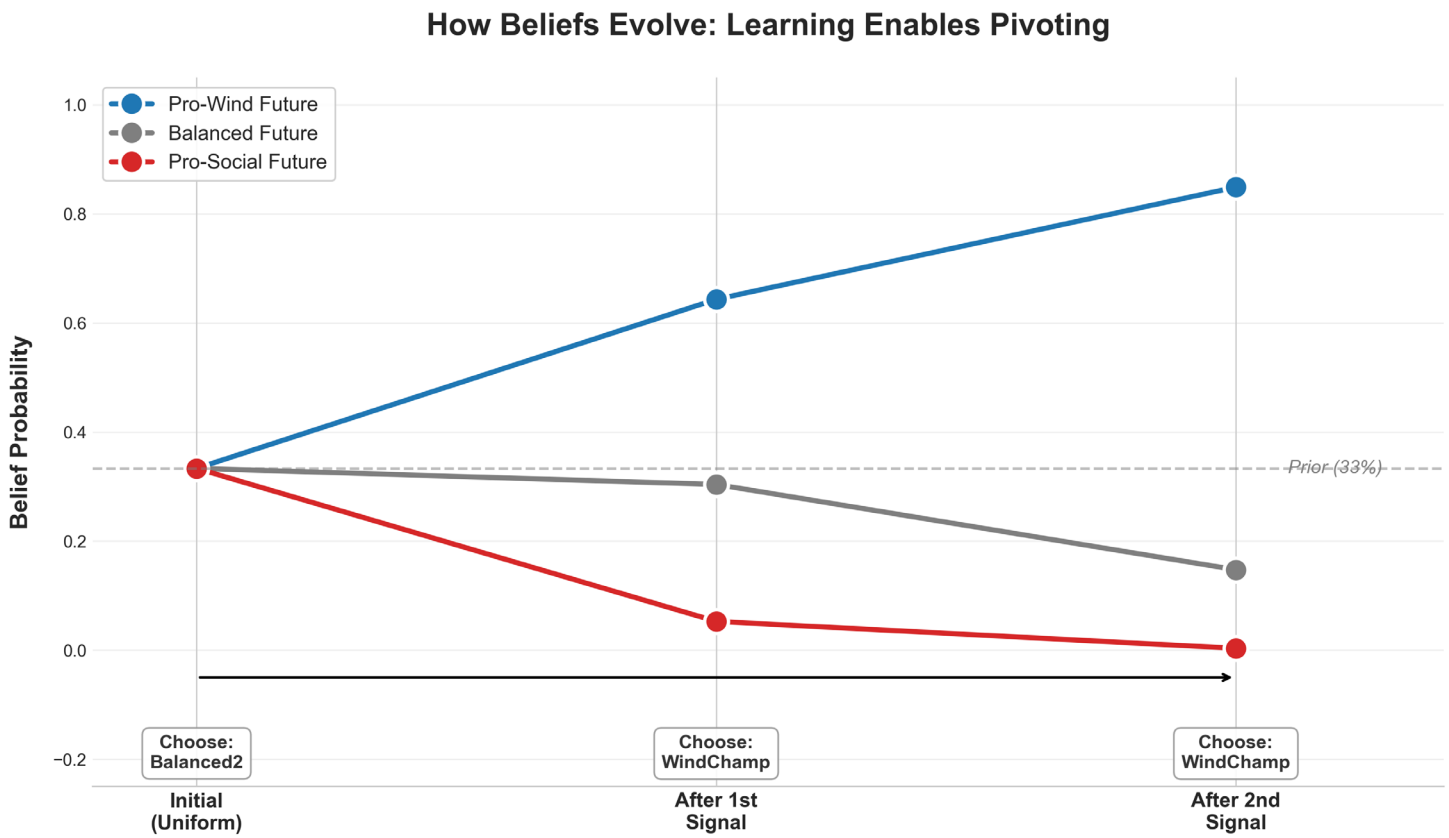
Sequential optimization with belief updating

Adaptive Planning Framework: Learn → Update → Pivot



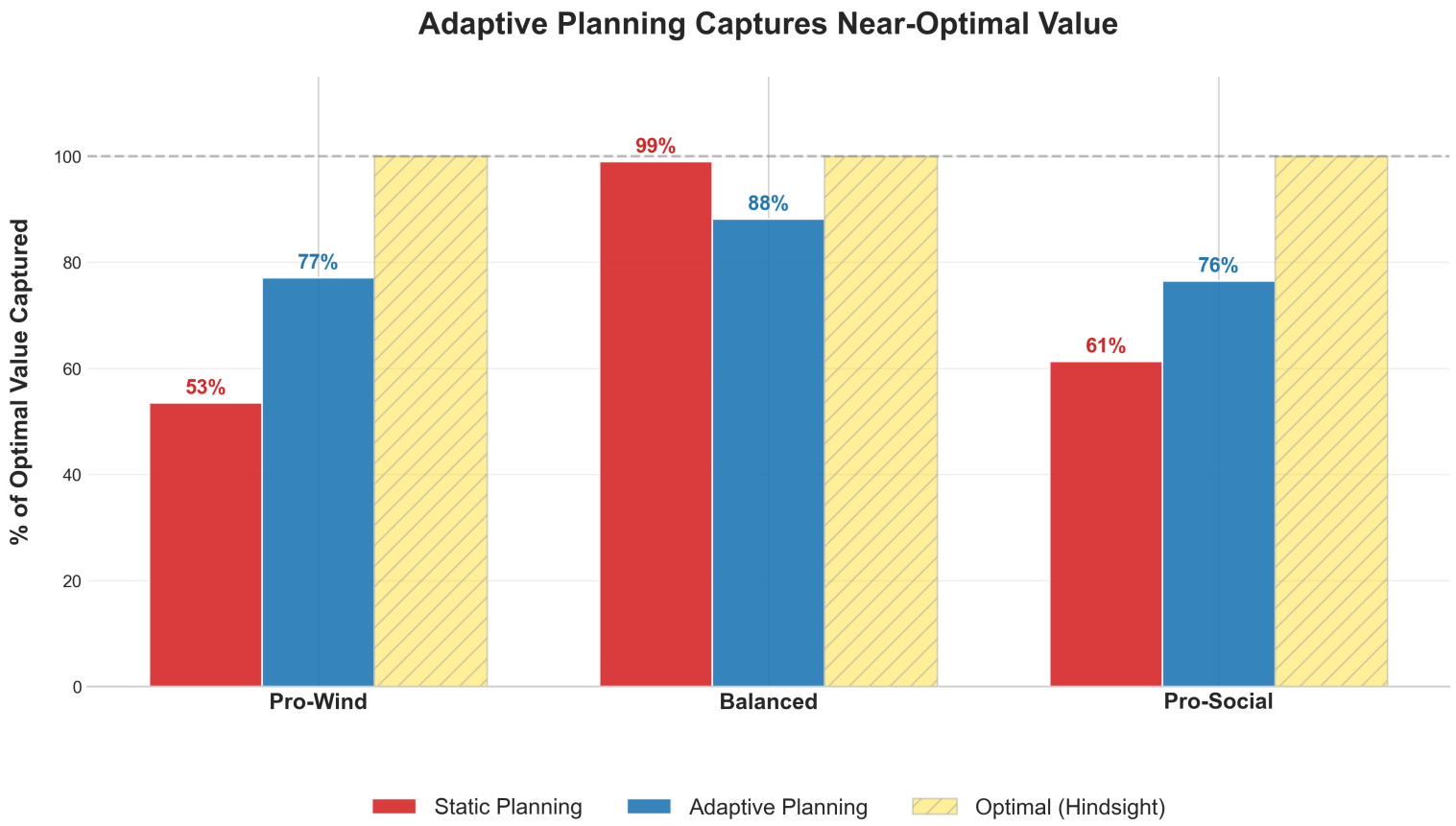
Belief Dynamics

Posterior convergence enables timely pivoting



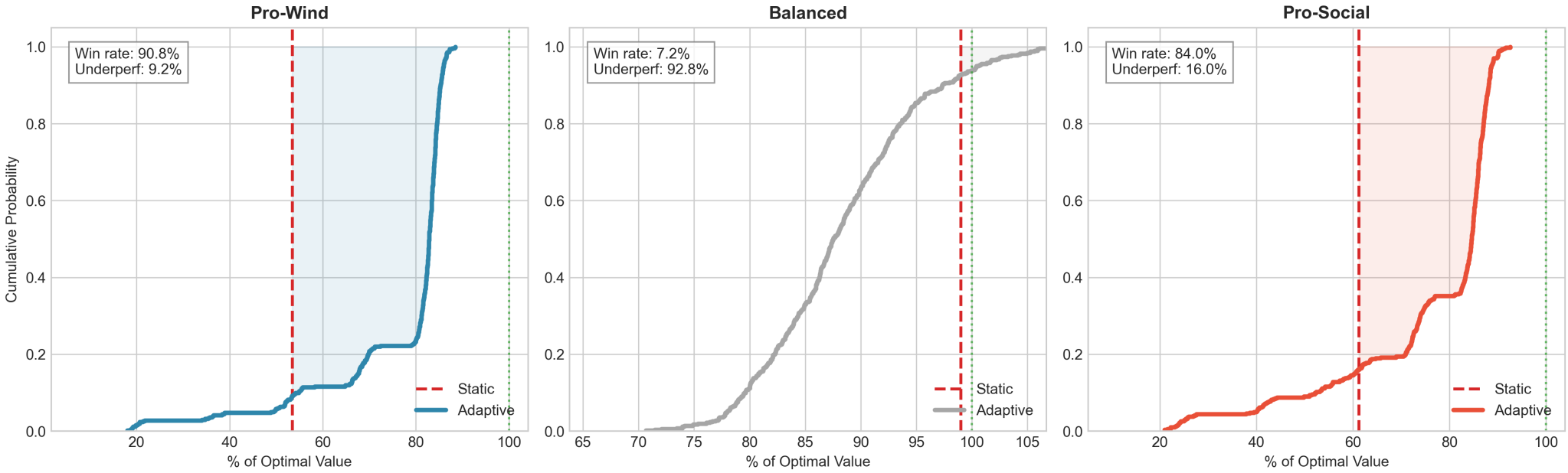
Performance Analysis

Adaptive captures 79% of optimal value on average, static captures 64%



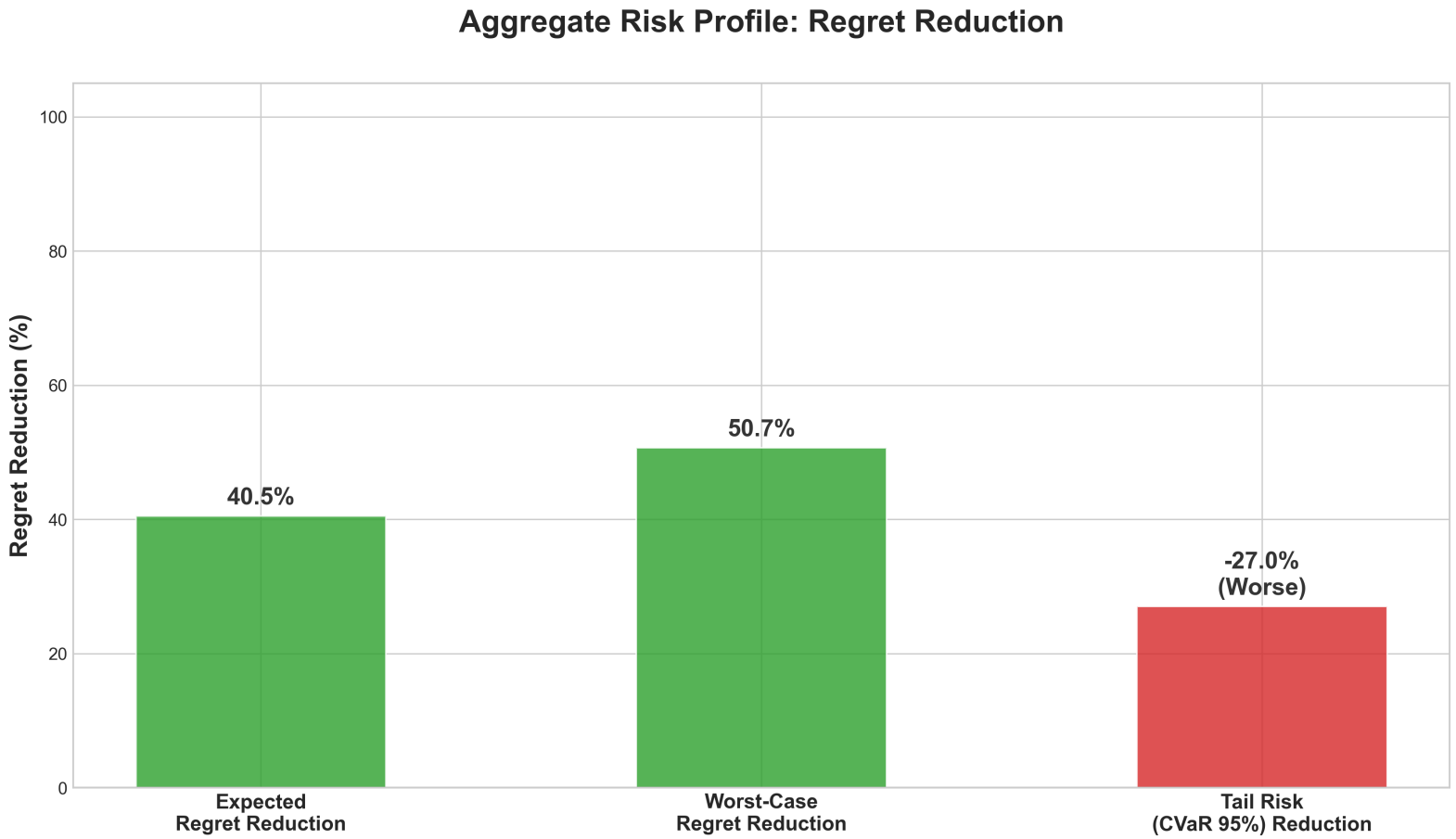
Empirical Robustness (Monte Carlo)

Win rate: 57% Underperformance rate: 36%



Aggregate Risk Profile

Expected Regret Reduction: 40% | CVaR(95%): -27%



Conclusions

- Sequential learning provides ~22.6% expected uplift vs static planning
- Adaptive outperforms static in 56.9% of simulations (MC n=500)
- First decision hedges; later decisions exploit learned information
- Framework applicable to any multi-stage decision problem under Bayesian uncertainty
- Next step: calibrate with Swiss case-study data and include switching/sunk costs

Thank you for your attention.

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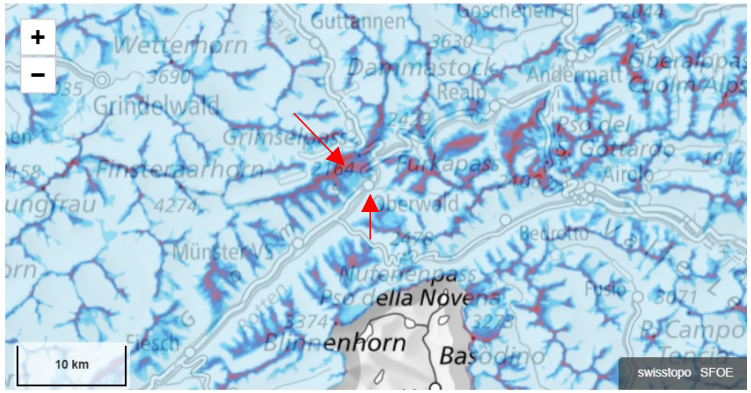
Wind speed



Full screen

< 4.0 m/s
≥ 4.0 - < 4.5 m/s
≥ 4.5 - < 5.0 m/s
≥ 5.0 - < 5.5 m/s
≥ 5.5 - < 6.0 m/s
≥ 6.0 - < 6.5 m/s
≥ 6.5 - < 7.0 m/s
≥ 7.0 - < 7.5 m/s
≥ 7.5 - < 8.0 m/s
≥ 8.0 m/s

areas with wind-power potential

Full screen

Im Rahmen der Richtplanung abzuklärende Gebiete

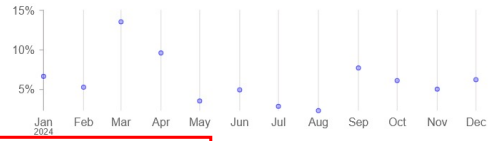
Gebiete mit hohem Windpotenzial

Die Analyse macht unterhalb von 1:50'000 keine Aussage.

Results: Wind power

Daily mean

Monthly capacity factor

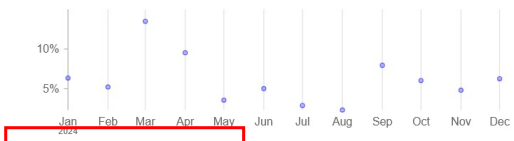


Total mean capacity factor: 6.14%

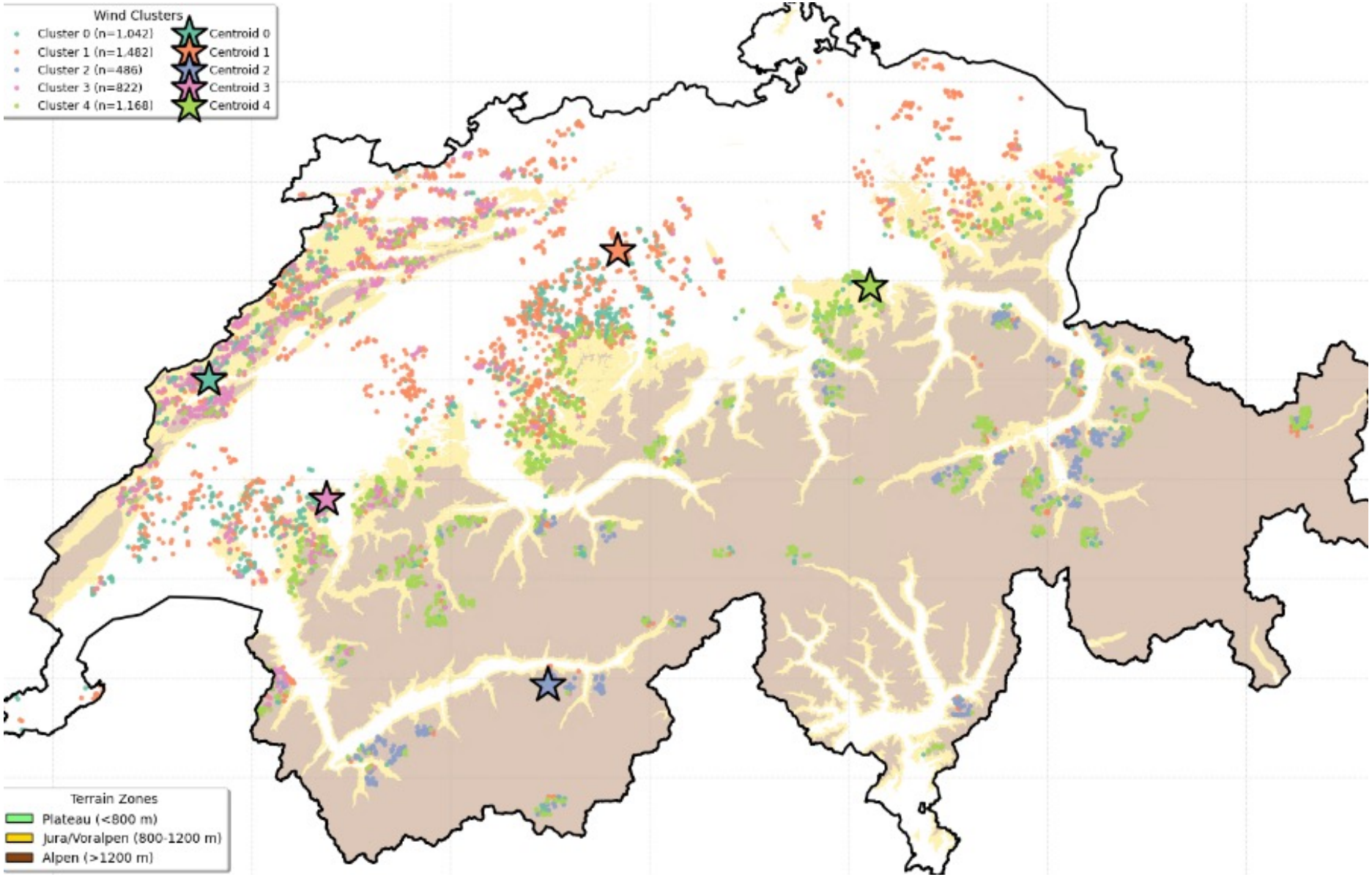
Results: Wind power

Daily mean

Monthly capacity factor



Total mean capacity factor: 6.10%


Wind Clusters
Cluster 0 (n=1.042)
Cluster 1 (n=1.482)
Cluster 2 (n=486)
Cluster 3 (n=822)
Cluster 4 (n=1.168)
Centroid 0
Centroid 1
Centroid 2
Centroid 3
Centroid 4
Terrain Zones
Plateau (<800 m)
Jura/Voralpen (800-1200 m)
Alpen (>1200 m)

Cluster profile ‘Magnitude’