Spatial strategies for siting variable renewable energy sources to ensure weather resilience in Switzerland

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ENERGY RESEARCH TALKS DISENTIS 2025

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Disentis, Switzerland

Resilience of an electricity system with a high penetration of weather-dependent renewables

Fully weather-dependent:
- Solar PV
- Wind power

Partially weather-dependent:
- Hydropower

Not dependent on weather:
- Biomass
- Geothermal

Siting strategies?

Storage?

Is a renewables-based electricity system resilient to different weather conditions?

Continental balancing?

Gas backup?

Background: weather resilience of renewable electricity systems

Two approaches:

- Designing a system which is resilient to decades of historical weather patterns *Zeyringer et al., 2018; Grochowicz et al., 2023; Killenberger et al., 2024*

Or:

- **Verify the weather reliability of an electricity system with a pre-defined capacity layout** *Collins et al., 2018; Grochowicz et al., 2024; Gotske et al., 2024*

RESEARCH GAP 1:

- Weather modelling at sub-national resolution (resilience is first scope of national policy, and higher resolution captures the role of weather impacts more precisely)

Background: weather resilience depends also on the location of variable-renewable energy systems (VRES) plants

- Siting by **cost-effectiveness** *Zeyringer et al., 2018*
- Tradeoffs between **cost-effectiveness** and **regional equity** *Sasse et al., 2019*
- Represent the **current trends** in models *Thormeyer et al., 2020*
- Wisely allocated VRES plants can counter-balance weather patterns *Grams et al., 2017*

RESEARCH GAP 2:

- Broad study on how different sitings of renewables technologies affect weather resilience (i.e. siting by cost-efficiency, by equity, by allowing continuation of current trends

Switzerland as a case study

- Spatial studies indicate uneven distributions of PV and heat pumps installations across the country (**current trends**)

  Zielonka et al., 2024; Zhang et al., 2023
- Current trends do not coincide with **cost-effective** nor with **even siting** of renewables.

  Sasse et al., 2019

- Swiss national referendum (June 2024): implement a target of 35 TWh/year generation from non-hydro renewables by 2035.

  https://www.strom.ch/fr/grands-axes/loi-pour-lelectricite-mantelerlass

- Small country: facilitates sub-national modelling at high resolution
- Peculiar topology (mountains, valleys, plateaus), and at the center of European grid

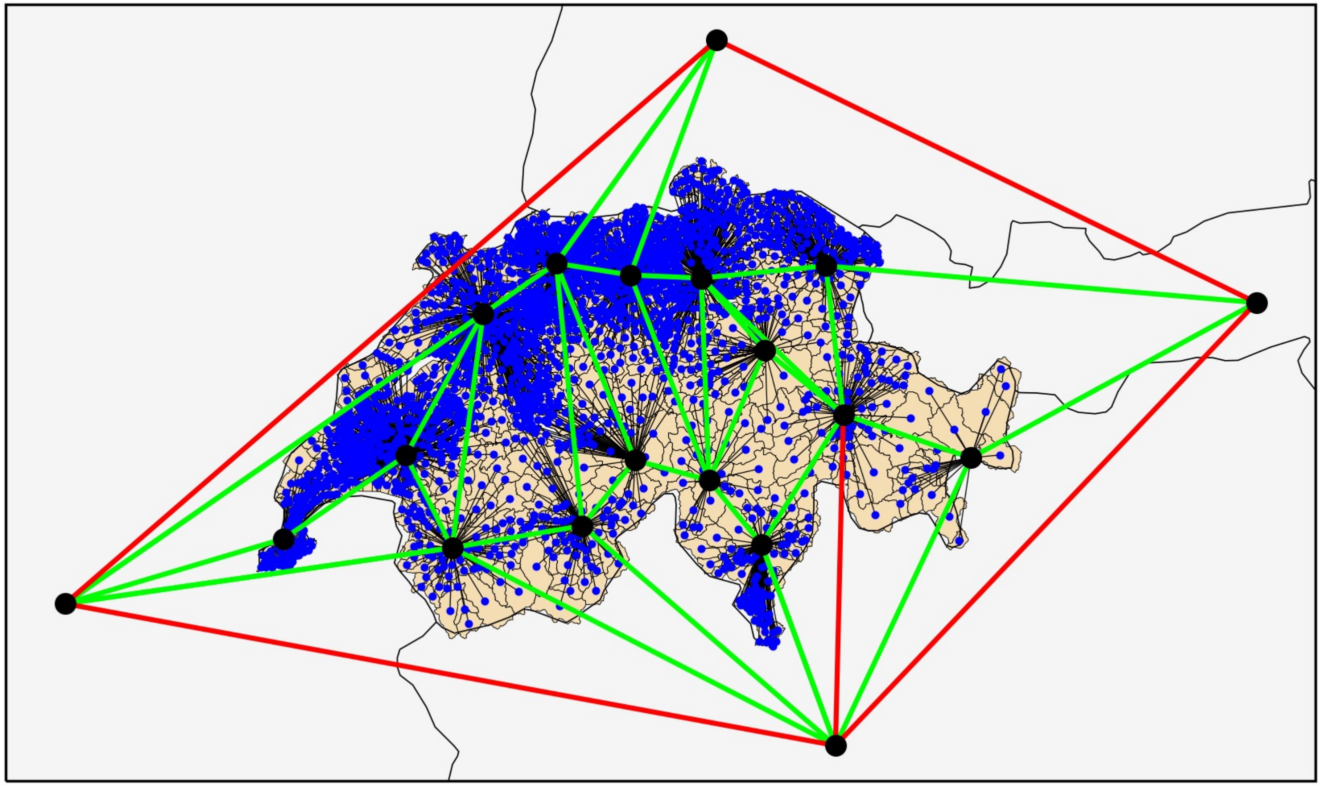
RESEARCH QUESTION:

- (i) How the implementation of the target of 35 TWh/year of renewable electricity and (ii) VRES siting strategies perform in terms of weather resilience?

Methods: EXPANSE electricity model

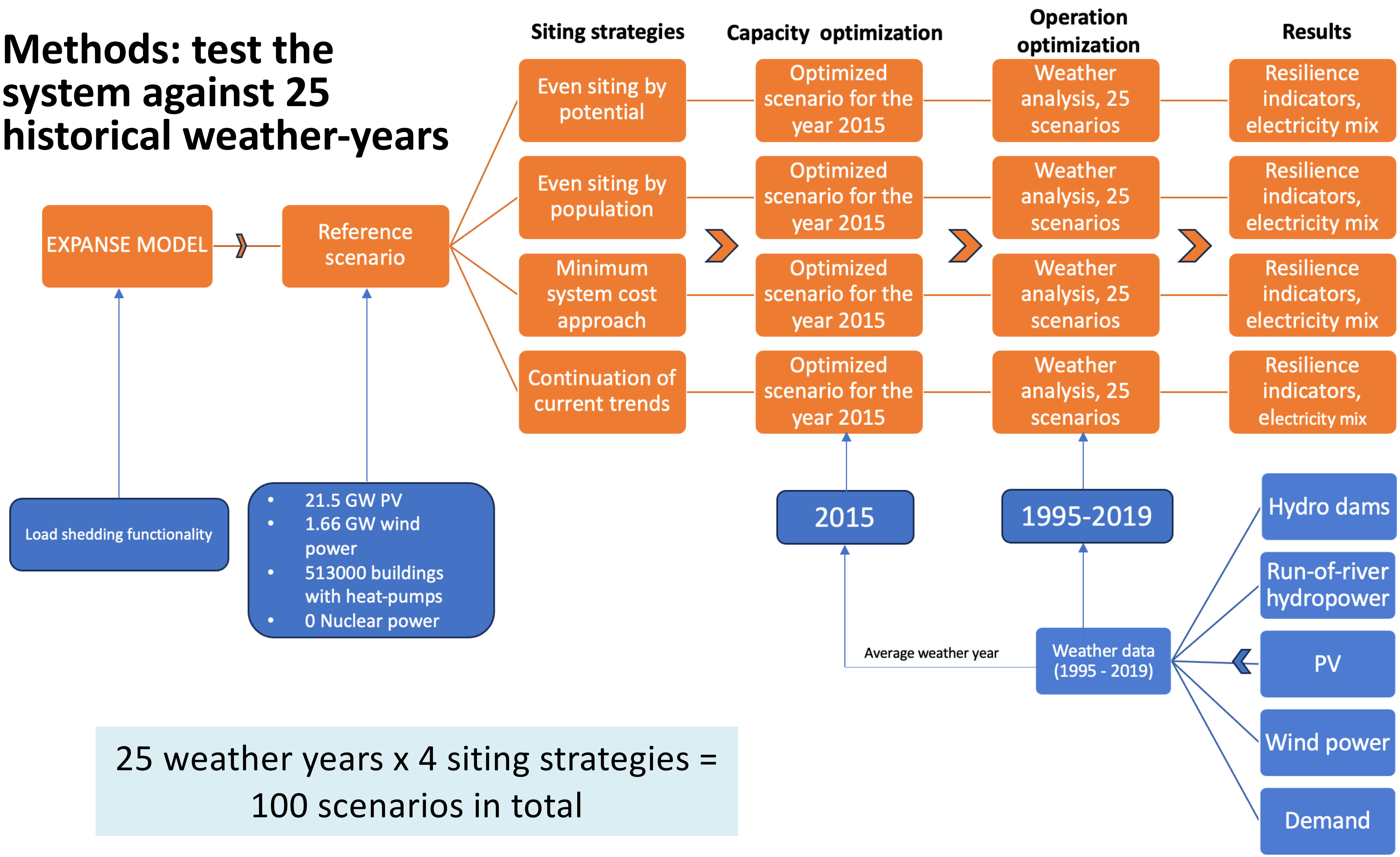
- 5 countries, Switzerland + neighbouring countries
- Spatial resolution of 2136 Swiss municipalities
- 3 hours temporal resolution, year 2035

- It models generation, transmission, storage and demand of electricity
- Minimisation of total system cost



Sasse and Trutnevyte 2019; Sasse and Trutnevyte 2020; Sasse and Trutnevyte 2023 (a), (b)

Methods: test the system against 25 historical weather-years



25 weather years x 4 siting strategies = 100 scenarios in total

Methods: Siting strategies

Spatial resolution of 2136 Swiss municipalities

Installed capacity	Solar PV 21.5 GW	Wind power 1.66 GW	Heat pumps 513000 buildings
Even siting by population	Proportional to population	Proportional to population	Proportional to population
Even siting by technical potential	Proportional to technical potential	Proportional to technical potential	Proportional to technical potential
Minimum system cost approach	Minimises total system costs	Minimises total system costs	Proportional to technical potential
Expected siting (continuation of current trends)	Probabilistic projections based on current trends*	Spillover effect	Probabilistic projections based on current trends*

* Zielonka et al., PNAS Nexus 2 (2023)

Methods: Weather data collection

- Switzerland (municipality resolution)
- Neighbouring countries (country average value)
- 25 historical years: 1995-2019

Technology	Source (Switzerland)	Source (Neighboring countries)
Solar PV	Renewables ninja https://www.renewables.ninja	Renewables ninja
Wind power	Renewables ninja	Renewables ninja
Run-of-river	Dujardin et al, Calliope model https://www.callio.pe	Calliope model, IEA*
Hydropower dams	Linear regression	Calliope model, IEA*
Electricity demand (heat-pumps)	Developed a bottom-up model (temperature from renewables ninja)	Entso-E**

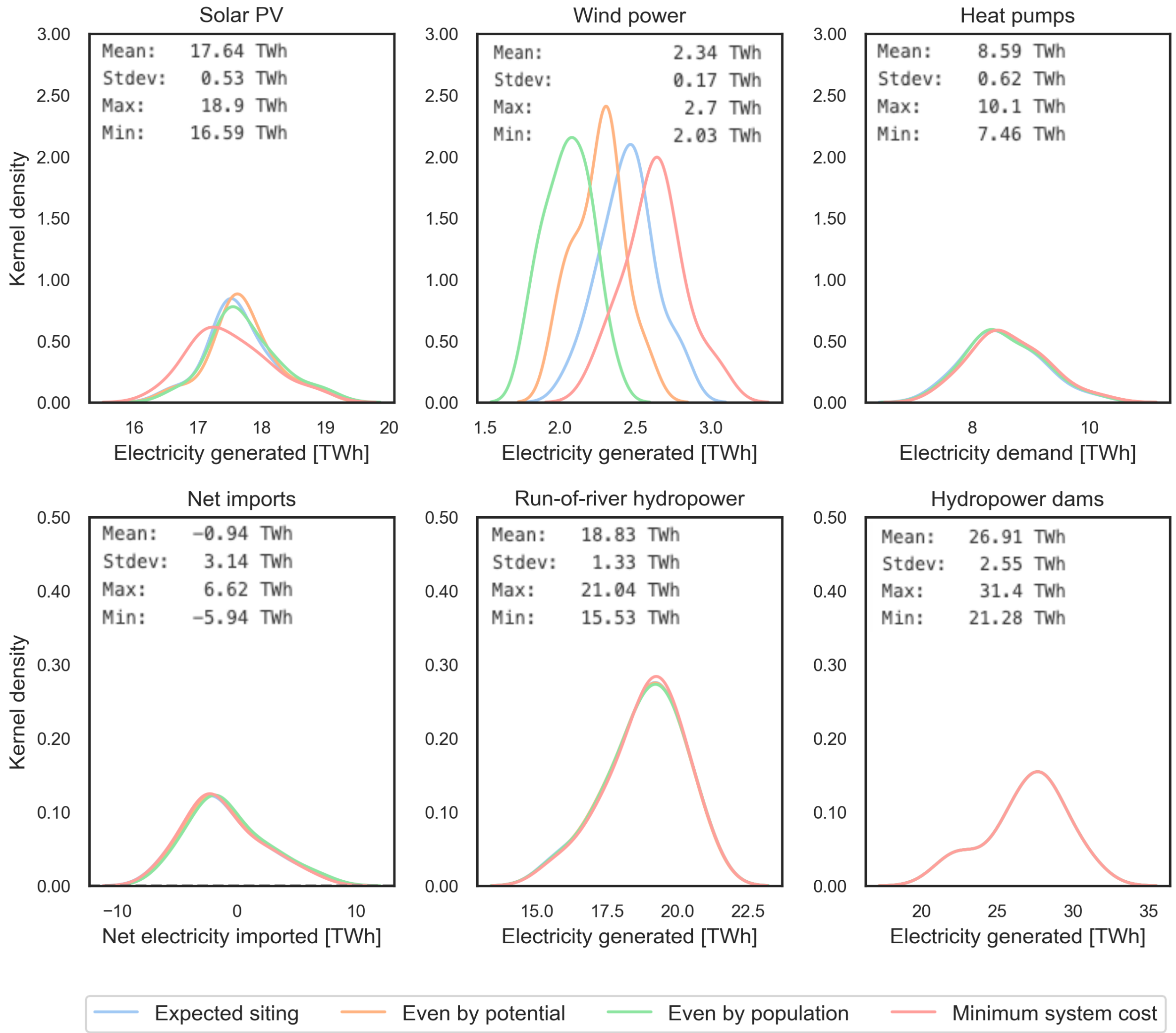
* https://www.iea.org/data-and-statistics/data-tools/hydropower-data-explorer
**https://2022.entsos-tyndp-scenarios.eu/download/

Methods: resilience indicators

Resilience indicator	Definition
Diversification of electricity supply [-]	Shannon index $\sum_{i=1}^{n} p \cdot \ln(p)$, where p is the share of electricity generated by each technology
Decentralization index [-]	Ratio of the electricity generated by decentralised sources to total domestic electricity generation
Import dependency [-]	Ratio of net electricity imports to total domestic electricity generation
Self-sufficient electricity supply [h]	Number of hours per year in which domestic supply is equal or higher than the electricity demand
Total generation from renewable sources [TWh]	Electricity generation from solar PV, biomass and waste, wind power, run-of-river hydropower, and hydro dams.
Hours of load shedding above 1% load [h]	Number of hours per year in which more than 1% of the demand load is not supplied
Hours of load shedding above 5% load [h]	Number of hours per year in which more than 5% of the demand load is not supplied
Equivalent availability factor for solar PV [-]	$\frac{electricity\ produced}{electricity\ produced + curtailed}$
Equivalent availability factor for wind power [-]	$\frac{electricity\ produced}{electricity\ produced + curtailed}$

Results:

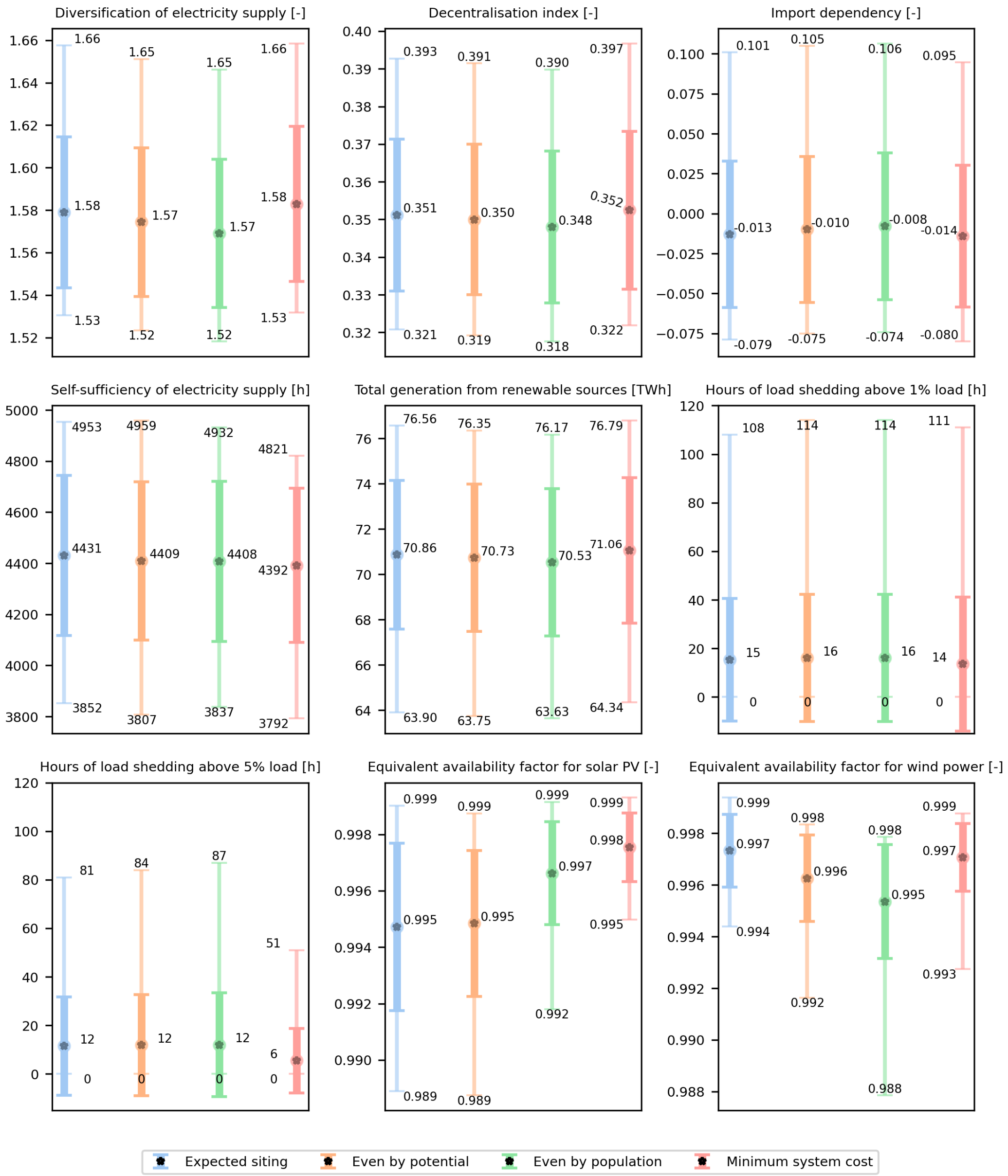
Supply mixes under conditions of historical weather years



- **Solar PV and wind** production very robust to weather
- **Heat pump** demand range ≃2.5 TWh
- **Net imports** range ≃12 TWh
- **Hydropower** has a larger variance than PV and wind

- **Different sitings** affect solar PV and wind power generation

Results: Resilience indicators



- Share of ***decentralisation index*** ranges from about 32% to 39%
- *Expected* siting strategy: scores highest for ***self-sufficient supply***
- ***Hours of load shedding*** *(>5% load)*: "Cost-optimal" scores lowest
- *Cost-optimal* siting strategy is the most robust in terms of ***equivalent availability factor***
- **Minimum system cost siting strategy**: consistent, albeit minor, advantages for weather resilience

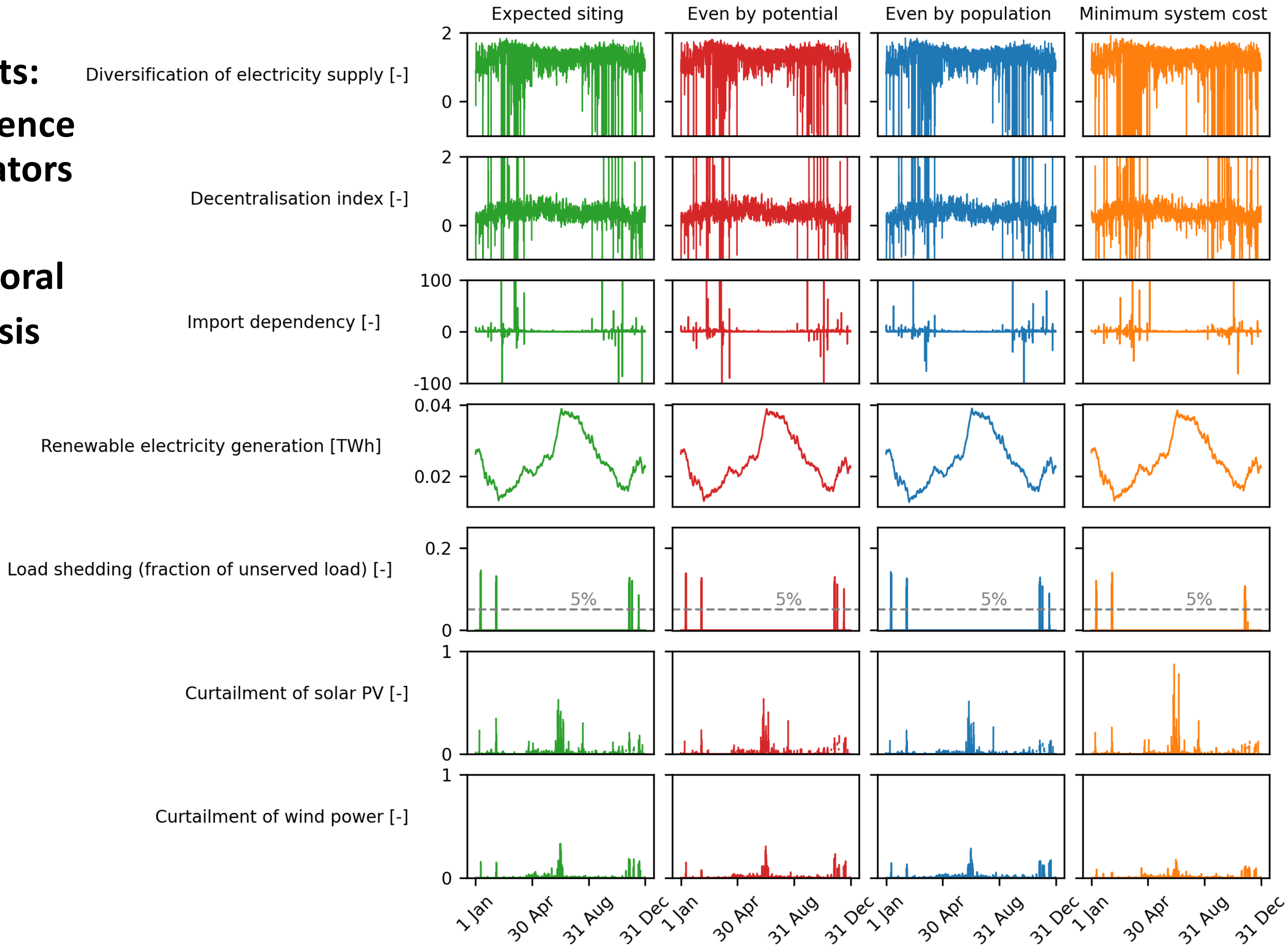
Results: Comparative assessment of the resilience indicators across 25 weather years

	Diversification of electricity supply	Decentralisation index	Import dependency	Self-sufficiency of electricity supply	Total generation from renewable sources	Hours of load shedding above 1% load	Hours of load shedding above 5% load	Equivalent availability factor for solar PV	Equivalent availability factor for wind power
1995	0.21	0.26	0.59	0.62	0.51	1	1	0.83	0.86
1996	0.41	0.49	0.3	0.35	0.21	1	1	0.96	0.89
1997	0.22	0.21	0.68	0.62	0.58	0.86	1	0.8	0.8
1998	0.21	0.31	0.56	0.6	0.48	1	1	1	0.95
1999	0.07	0.11	0.79	0.76	0.72	1	1	0.75	0.81
2000	0.06	0.17	0.94	0.94	0.88	1	1	0.96	0.93
2001	0.06	0.07	1	0.89	1	1	1	0.52	0.8
2002	0.34	0.36	0.68	0.64	0.57	1	1	0.67	0.85
2003	0.71	0.73	0.55	0.42	0.46	0.97	1	0.26	0.71
2004	0.34	0.33	0.68	0.7	0.63	0.68	0.65	0.81	0.76
2005	0.97	1	0	0	0	0.97	1	0.34	0.34
2006	0.78	0.73	0.33	0.15	0.25	1	1	0.51	0.79
2007	0.5	0.51	0.72	0.94	0.62	0.92	0.88	0.54	0.44
2008	0.15	0.16	0.83	0.92	0.79	0.95	1	0.33	0.59
2009	0.44	0.41	0.71	0.5	0.64	0.41	0.47	0.15	0.55
2010	0.43	0.3	0.47	0.45	0.47	0	0	0.49	0.68
2011	0.7	0.85	0.48	0.3	0.28	0.78	1	0.6	0.69
2012	0.43	0.35	0.74	0.68	0.67	0.43	0.29	0	0.56
2013	0.15	0	0.82	0.71	0.81	1	1	0.48	0.65
2014	0	0.07	0.97	1	0.83	1	1	0.87	0.93
2015	0.48	0.53	0.73	0.83	0.58	1	1	0.57	0.73
2016	0.82	0.69	0.28	0.09	0.14	1	1	0.55	0.79
2017	1	0.94	0.15	0.05	0.06	0.97	1	0.11	0
2018	0.43	0.41	0.83	0.62	0.65	1	1	0.82	1
2019	0.19	0.22	0.75	0.78	0.63	1	1	0.86	0.82

- **Weather-year 2010**: highest score for "hours of load shedding", low score of renewables generation, and high score in import dependency
- **Weather-year 2017:** highest generation from biomass and gas, low hydropower generation
- **Weather year 2001 and 2005:** interplay between import and hydropower (when one is maximum, the other is minimum)

Results: Resilience indicators

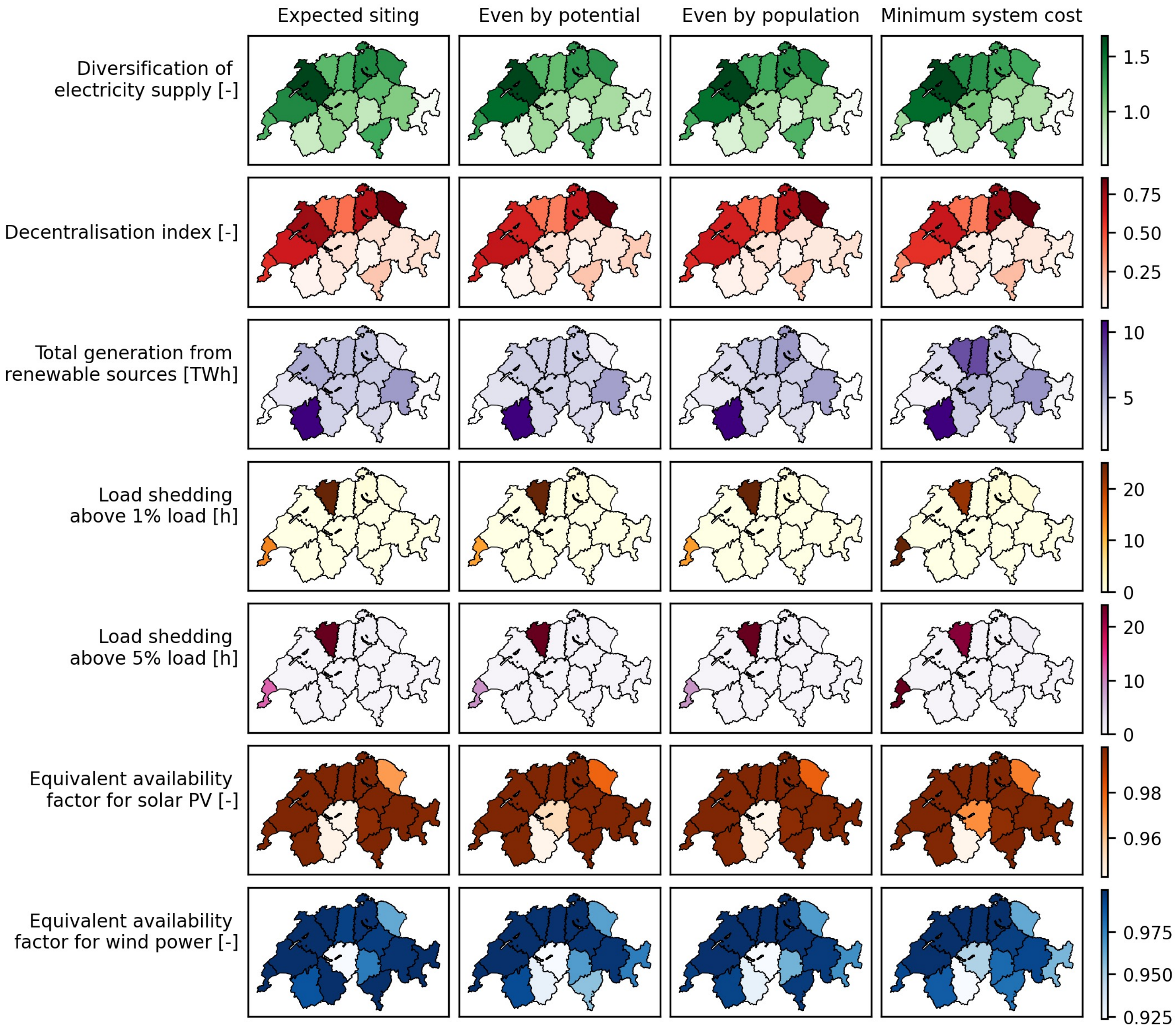
Temporal analysis



- Renewables generation peaks during summer
- Import dependency and load shedding increase during winter
- Most curtailment happens during Summer

Results: Resilience indicators

Spatial analysis



- Northen and Western Switzerland constibute to **diversification** and **decentralisation**
- **Renewable electricity generation** is rather uniform
- **Load shedding** happens in regions with no hydropower
- Most **curtailment** spatially localized in two regions in the south and on region in the Northeast

Conclusions

- The Swiss system that relies fully or almost fully on VRES is techno-economically operational and resilient to weather variations

- Solar PV and wind generation is robust to weather variations

- Weather variations were found to particularly affect electricity demand for heat-pumps and availability for hydropower, indirectly influencing electricity import and export

- The siting strategies analysed perform very similarly in terms of resilience: location of VRES is not a major issue for weather resilience

- **Technology siting decision should be guided by other technical, economic and environmental arguments**

Thank you for your attention!

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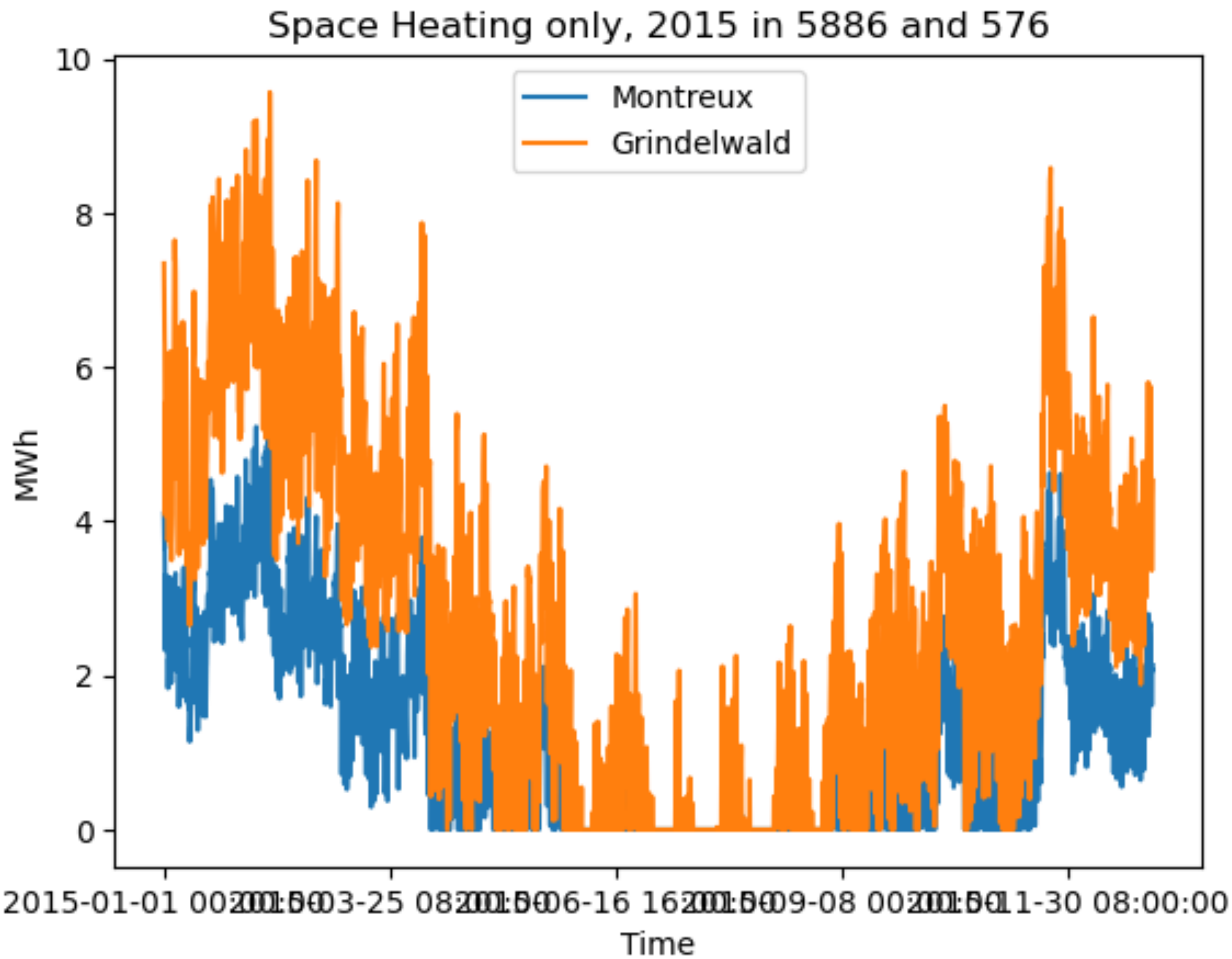
Backup slides

Limitations / further research needs

- Historical weather conditions VS future impacts of climate change
- Future electricity demand and flexibility from heat-pumps and electric vehicles
- Alpine PV
- More wind power potential exploitable
- H2 production at scale
- Switzerland has high hydropower availability and grid connection with neighboring countries: performance of siting strategies in other countries?

Electricity demand from heat-pumps:

Mountain VS Valley

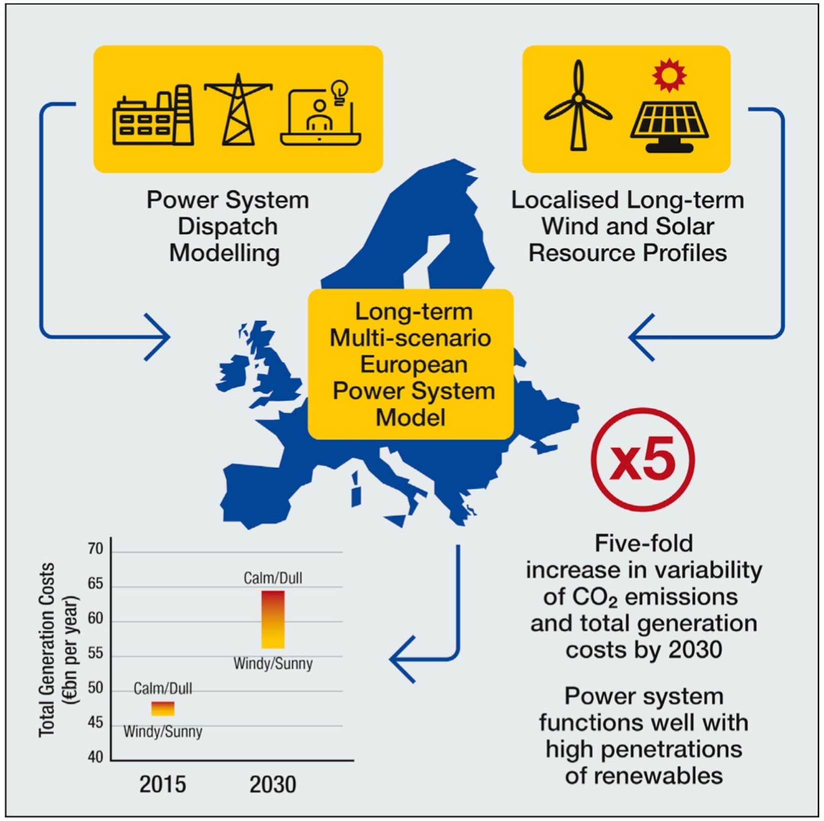


Literature review: Impacts of inter-annual wind and solar variations on the European power system

Joule, 2018, S. Collins et al

- European study
- Electricity market model (PLEXOS)
- **Spatial-explicit** PV and wind profiles for 30 historical years

- Ambitious decarbonisation 2030 targets lead to much greater influence of **weather patterns**
- Import and storage: "weather insurance" products

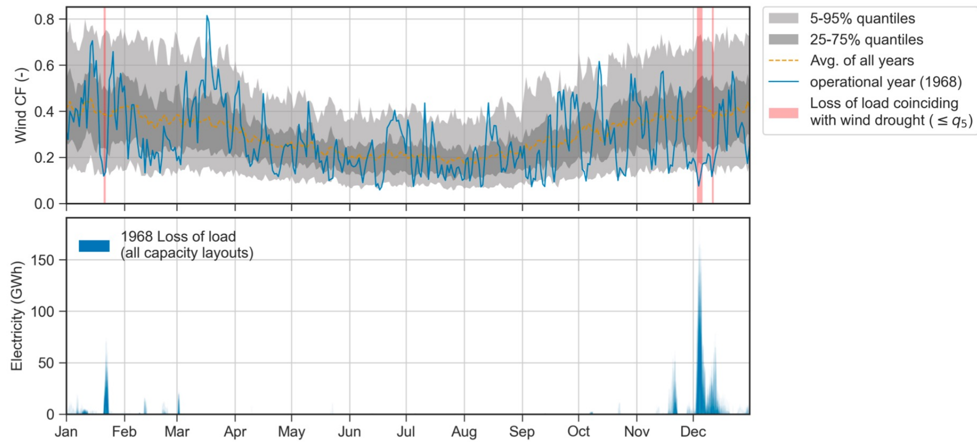


Literature review : Designing a sector-coupled European energy system robust to 60 years of historical weather data

Nature Communications, 2024, E. Gotske, F. Neumann, M. Victoria

- European Study
- Energy system model (pyPSA)
- 62 capacity layouts tested against 62 weather years (combines approaches)

- Extreme weather-years drive investments in robustness measures
- Unserved energy during winter periods (wind drougth)



RESEARCH GAP 1: WEATHER-RESILIENCE AT SUBNATIONAL SCALE

Literature review: siting of renewables is key to counter-balance weather variations

RES

- Different **weather-patterns** can differently impact optimal spatial allocations (Zeyringer, 2018, Nature Energy)
- Need accurate modelling of PV and Wind **location** and production (Simoes 2017)
- Interconnection of geographically disperse wind or solar PV farms
- Germany: interplay between wind farms in the North and solar PV in the South

Research questions (extra)

1) What is the impact of the expected / optimal / even spatial allocation of PV, wind, and HPs on the resilience of the Swiss electricity system, measured with 9 resilience indicators, and considering 25 historical weather-years?

2) What are the implications for the electricity generated?

3) Are there meaningful spatial or temporal patterns regarding points 1 and 2 ?

Methods: EXPANSE model

Objective function: capacity expansion + dispatchment

$$f_{\text{cost}} = \sum_{r,c} C_{r,c} G_{r,c} + \sum_{n,c} C_{n,c} H_{n,c} + \sum_{l} C_l F_l + \sum_t w_t \left[\sum_{r,c} o_{r,c,t} g_{r,c,t} + \sum_{n,c} o_{n,c,t} h_{n,c,t}^{\text{discharge}} + \sum_l o_{l,t} f_{l,t}^{+} \right]$$

Constraints

- Supply = demand in all grid nodes
- Kirchoff voltage law
- Powerplants operation (e.g. minimum baseload power, weather dependency)
- GHG emissions and renewable electricity targets
- …

Methods: Heat-Pump electricity demand

$$HP\ electr\ demand_{w-year}(s,t) = \left(\frac{1}{COP}\right) * (Hot\ water(s) + Space\ heating_{w-year}(s,t))$$

Hot water(s) = 5347.615 MJ/person ∗ number of people in 2035 in municipality(s) ∗ used potential [%] $_{expected/even}$ (s)

$$Space\ heating_{w-\ year}(s,t) = q\ *\ NumHP_{expected/even}(s) * HDD_{w-year}(s,t)$$

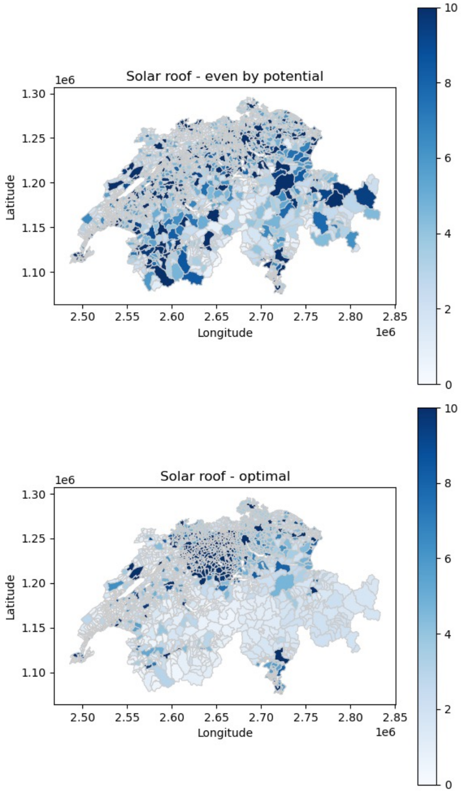
$$q = \frac{Heat\ consumed\ by\ heat\ pump\ in\ 2019/year}{number\ of\ HP\ in\ 2019\ * \sum_t avg(HDD(s))\ in\ 2019} \approx 0.001\quad [\frac{MWh/year}{1\ HP\ *1HDD}]$$

$$s = 2136\ municipalities$$
$$t = 8760\ time\ slices$$

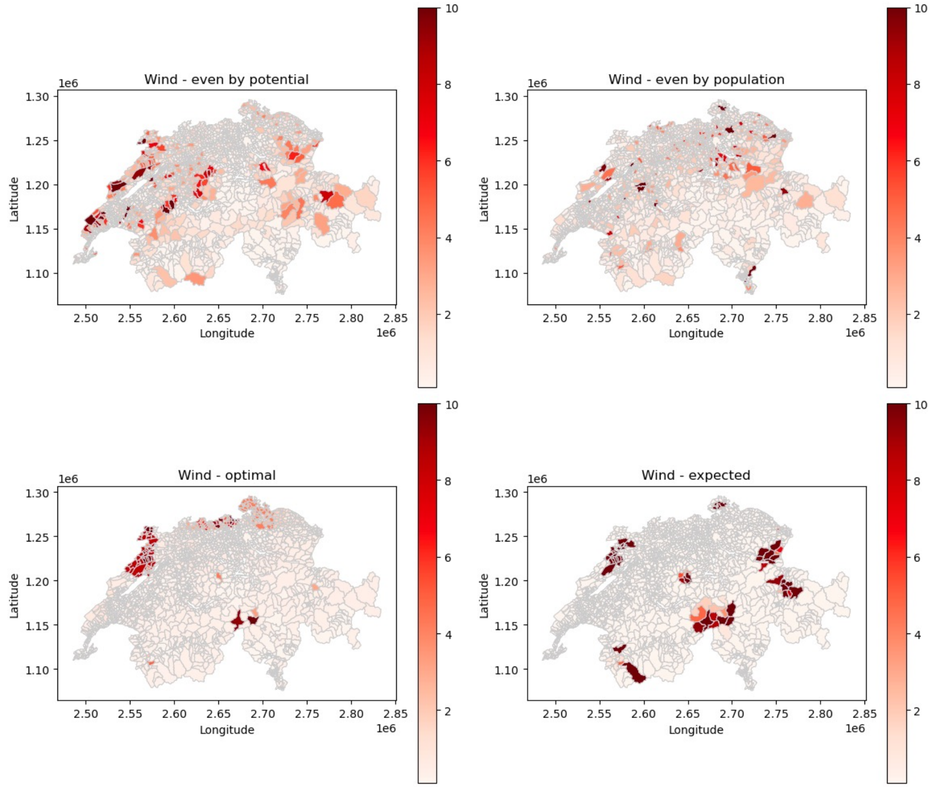
HDD threshold: 12°C
COP = 3.5

Methods: Siting Strategies

Solar PV

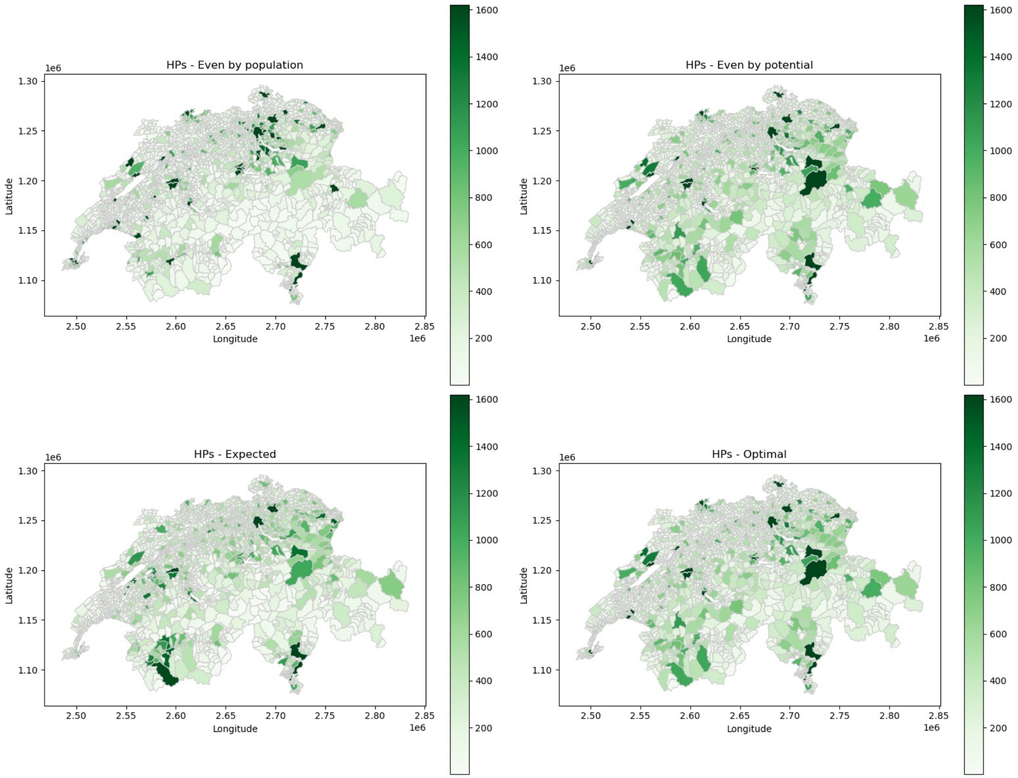


Wind power



Methods: Siting Strategies

Heat-pumps



Methods: capacity layout

- International HV lines, increase from 52 GW (current value) to about 62.4 GW
- Domestic HV lines, increase from 97.5 GW to 106.7 GW
- No investment on H2 and grid-scale battery
- 2.725 GW Biomass installed in Switzerland
- Neighboring countries meet the targets of CO_2 emissions and renewables production

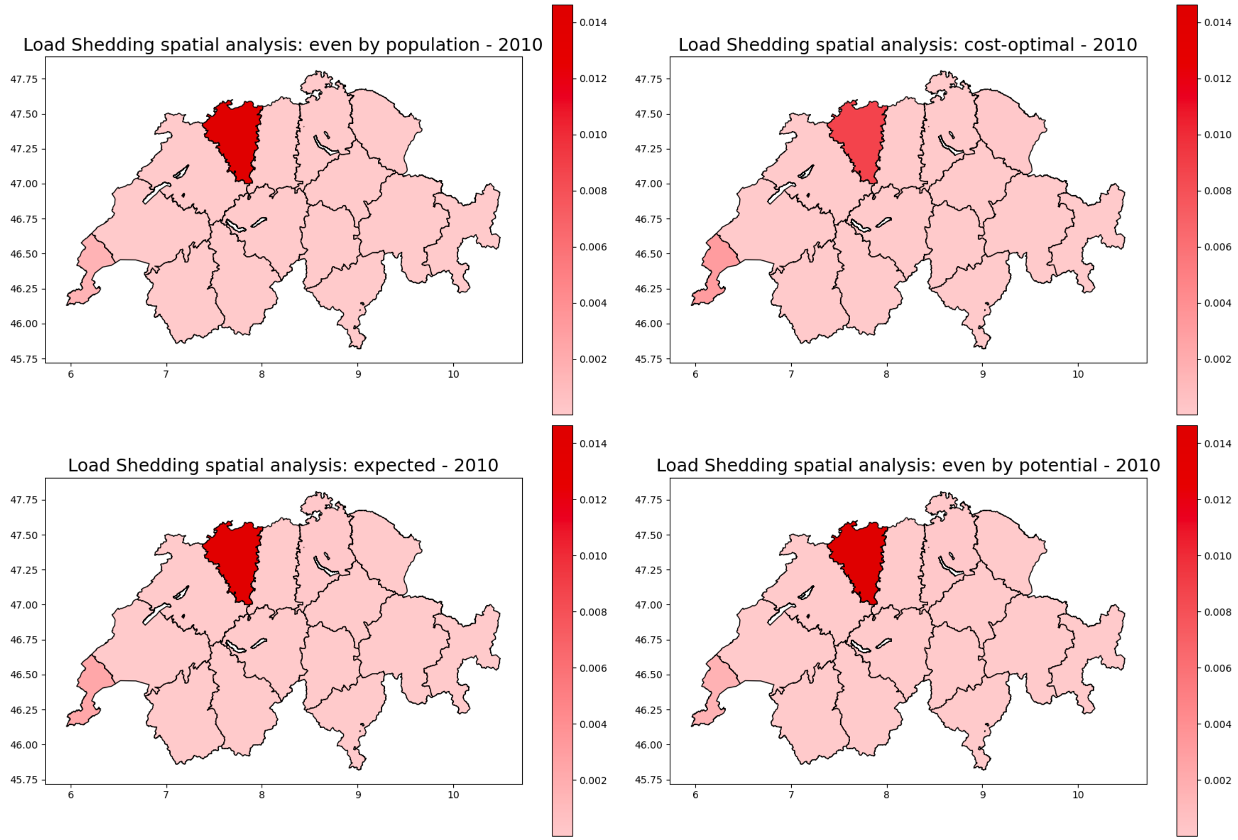
Resilience indicators [RQ1]

Hours of lost load (minimum 5% case)

Most challenging weather: 2010

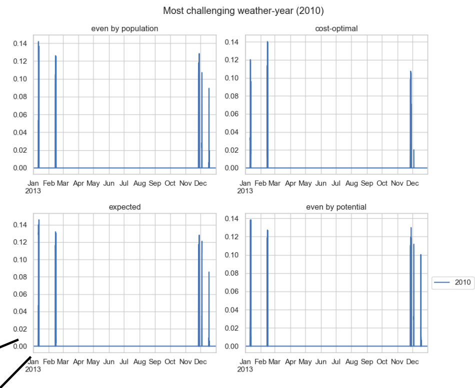
	even by population	cost-optimal	expected	even by potential
1995	0	0	0	0
1996	0	0	0	0
1997	12	0	12	12
1998	0	0	0	0
1999	0	0	0	0
2000	0	0	0	0
2001	0	0	0	0
2002	0	0	0	0
2003	12	0	9	9
2004	18	18	18	18
2005	0	0	0	0
2006	3	0	3	3
2007	3	6	0	3
2008	33	0	27	30
2009	33	27	33	36
2010	87	51	81	84
2011	6	0	9	6
2012	60	36	60	60
2013	0	0	3	3
2014	0	0	0	0
2015	3	0	3	3
2016	21	0	21	18
2017	9	0	9	12
2018	0	0	0	0
2019	0	0	0	0
mean	12.0	5.52	11.52	11.88
stdev	21.35	13.27	20.25	20.83

Results: spatial analysis of “Load shedding” indicator (5% threshold)

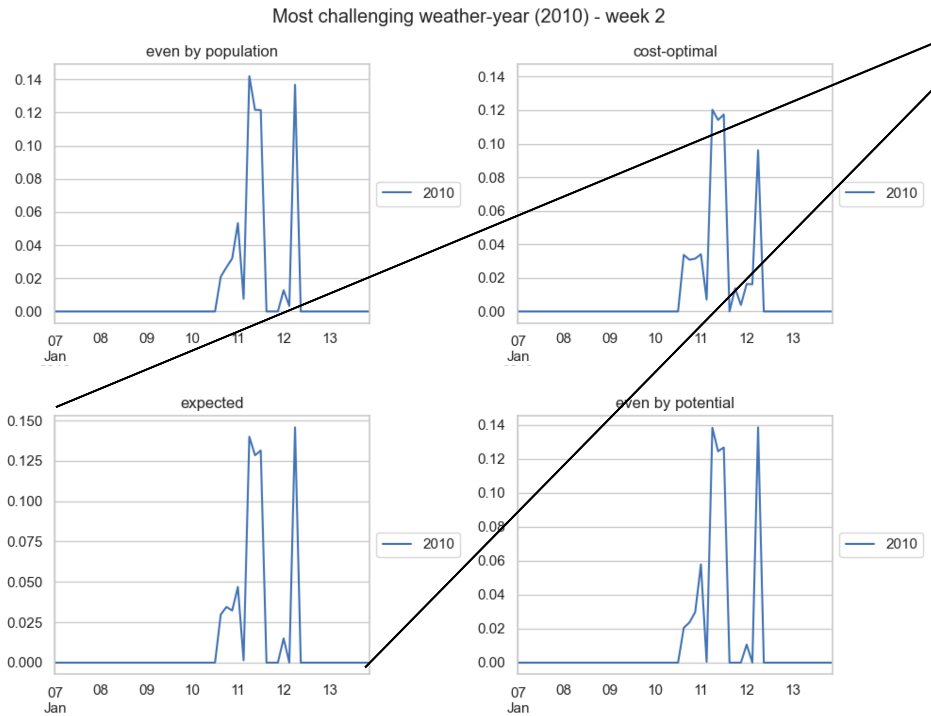


Regions with no hydro storage potential

Load shedding temporal analysis [RQ3]



Weather-year 2010



Most challenging weather year

Shannon Index