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# WP 4: Future Supply of Electricity - Highlights, Impacts and Outlook

**Peter Burgherr – WP4 Coordinator – Paul Scherrer Institute (PSI)**

T4.1: Prof. Dr. Stefan Wiemer, SED/ETHZ

T4.2: Dr. Peter Burgherr, PSI

T4.3: Prof. Dr. Michael Stauffacher, ETHZ

**SCCER SoE Annual Conference, Horw (LU), 13.09.2018**

# WP4: Tasks, Activities, Objectives

## Future Supply of Electricity

### Risk, Safety & Societal Acceptance

- Assist & enable upcoming P&D projects in DGE
- Move to risk-cost-benefit analysis and MCDA
- Validate & extend approaches and tools
- Engage with industry and cantonal regulators
- "Export" methodologies

### Global Observatory of Electricity Resources

- Technology monitoring; contributions to ES2050
- Sustainability Assessment using (spatial) MCDA
- Electricity Market in Europe and impacts in CH
- Electricity capacity expansion in CH, incl. Europe
- Stochastic dispatch optimization of hydropower
- Scenarios for fully renewable CH

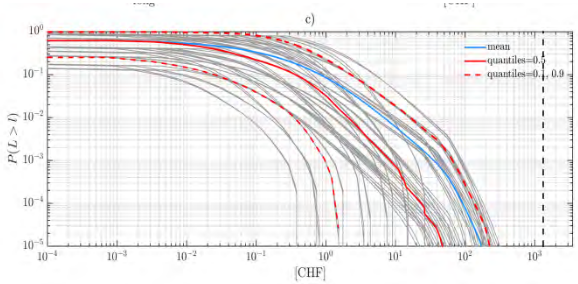
### JA S&M

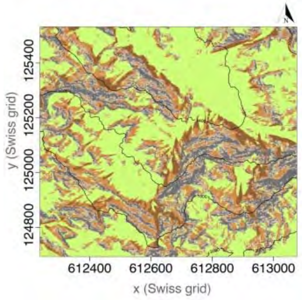
(G. Guidati)

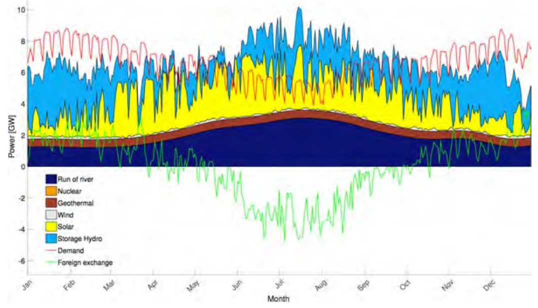
### Socio-Economic–Political Drivers

- Economic, social, and political boundary cond.
- Assessment of different policy futures for Swiss electricity supply
- JA IDEA with CREST

# T4.1 – Risk, Safety and Societal Acceptance







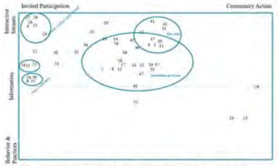


Fig. 1: Wider spaces of participation formats – program managers' perspective

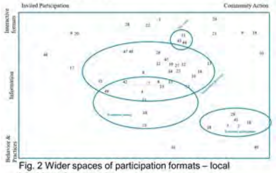
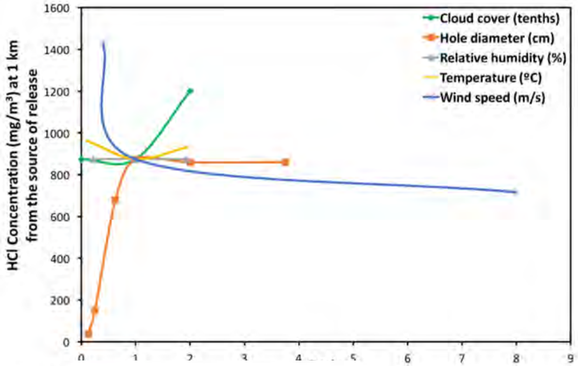
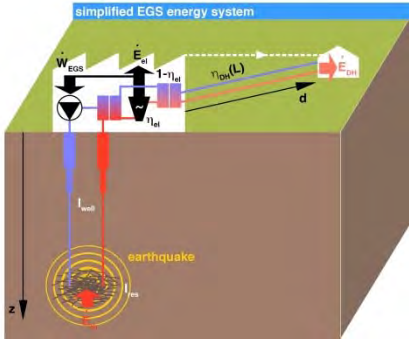
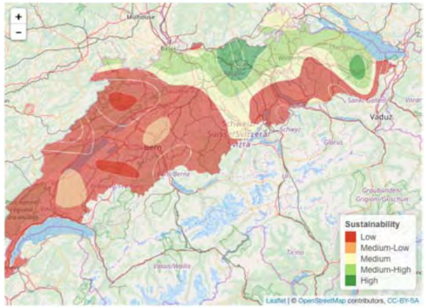
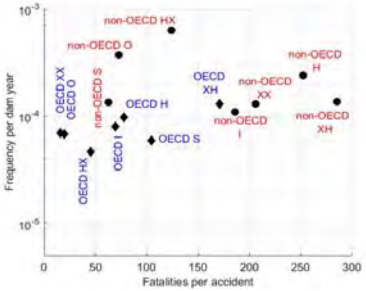


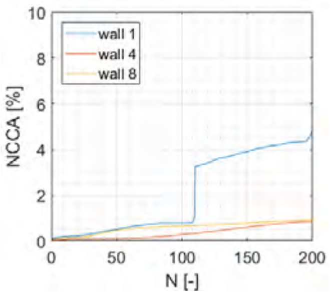
Fig. 2 Wider spaces of participation formats – local inhabitants' perspective

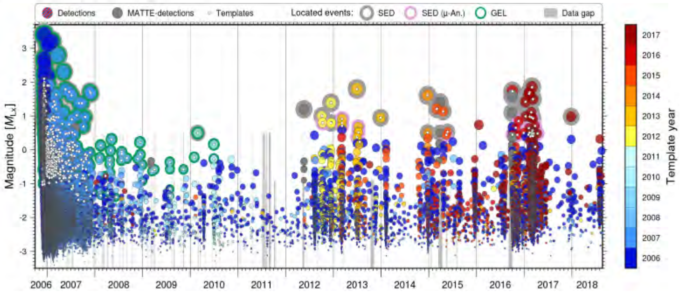


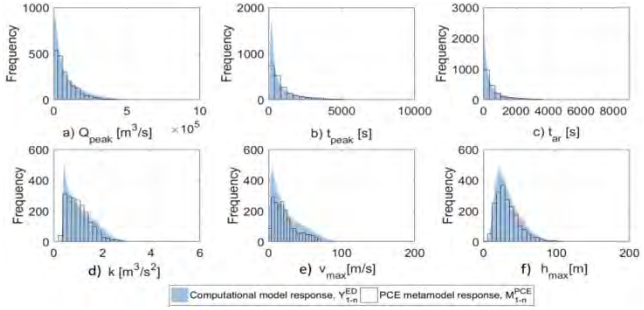








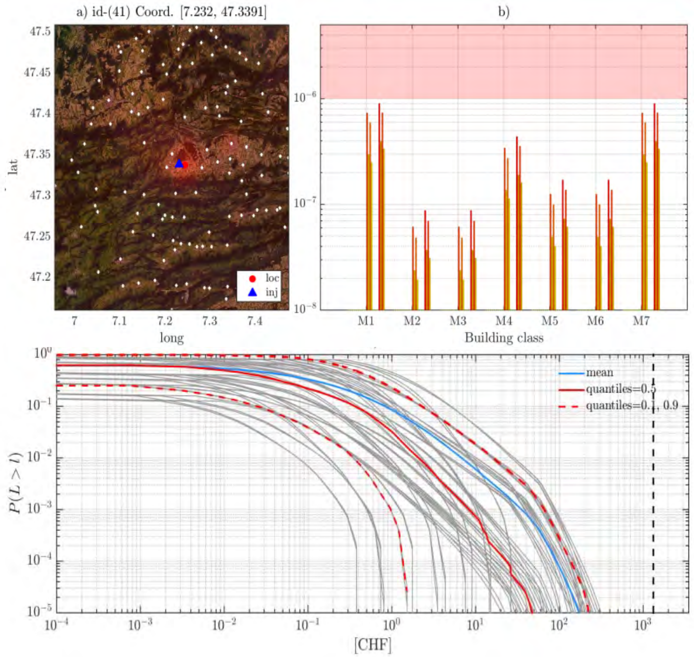




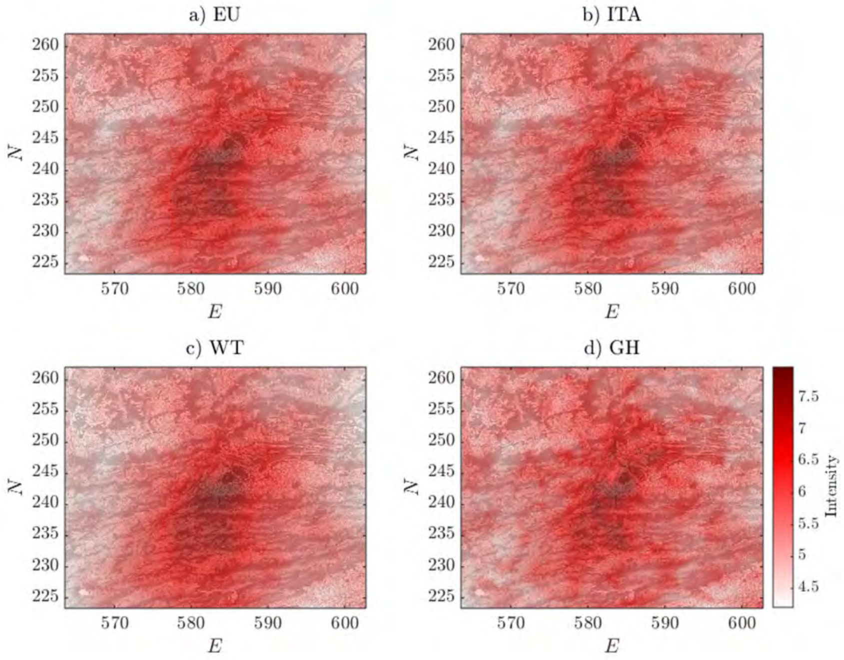
# Haute-Sorne DGE risk analysis validation

- Benchmarking of Haute-Sorne DGE risk analysis (in Matlab, R, Python OpenQuake)
- Aggregate probabilistic risk curves corrected for spatial correlation aspects

Local losses & individual risk

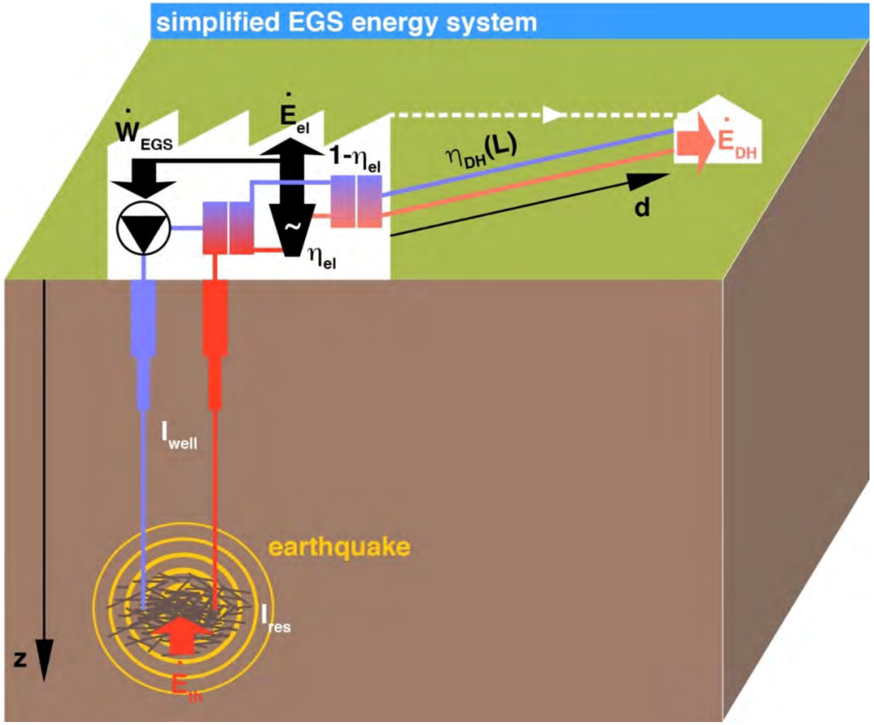


Aggregate losses via simulations



Broccardo et al., to be submitted

# DGE energy/risk governance meta-model



Mignan et al., injecting seismic risk mitigation measures into the Levelized Cost Of Electricity of Enhanced Geothermal Systems, in revision

- *Energy model:* analytical, both electricity and heat production modelled
- *Economic model:* LCOE reformulated to include "cost of public safety" (financial losses linked to seismic risk mitigation, such as loss of injection well during TLS)
- *Seismic risk model:* Probabilistic, safety-norm in risk space, safety-norm-based TLS
- *Behavioural model:* Cumulative Prospect Theory to model risk/loss aversion

- Maps optimal trade-off between public safety (via norm) & energy safety (via LCOE spatial minimization) to improve governance

# Identifying spaces of participation

- Research with the GEothermie 2020 program
- Worked on the different implicit assumptions about what is participation
- 6 focus groups with inhabitants and participatory observation management meetings
- Result indicate that program managers see participation as classical formats of information provision and site visits;
- Invited/internal participation that is exclusive is important in managers' view.
- Focus group participants see information provision as one important format
- They often referred to individual actions and awareness on an individual level.

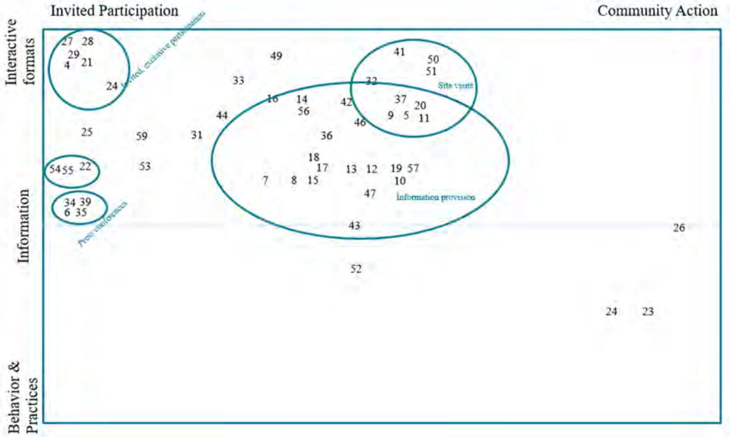


Fig. 1: Wider spaces of participation formats – program managers' perspective

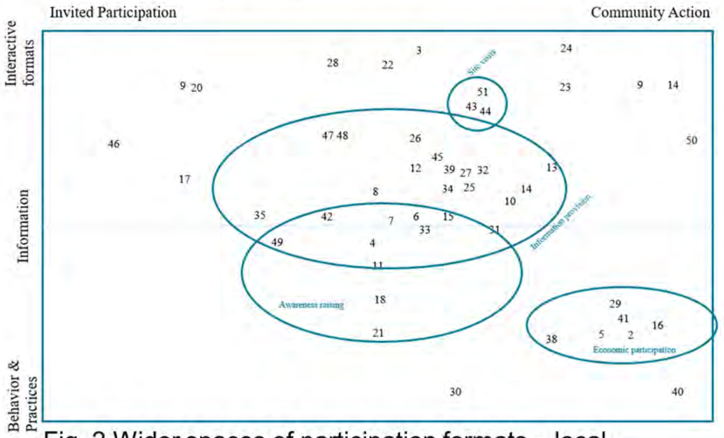
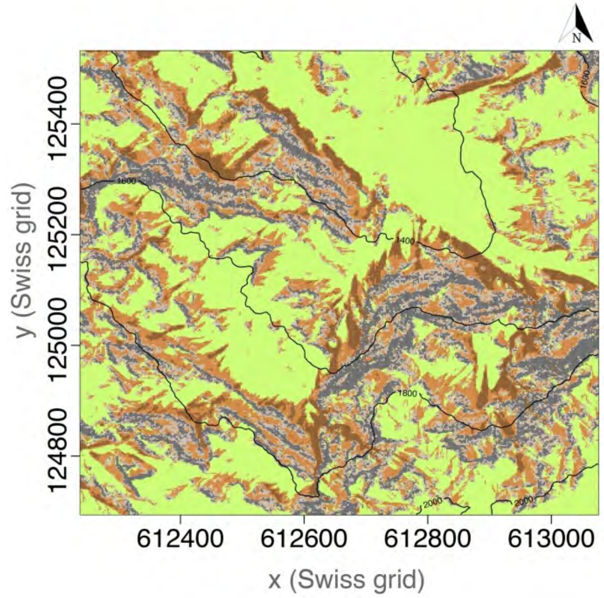
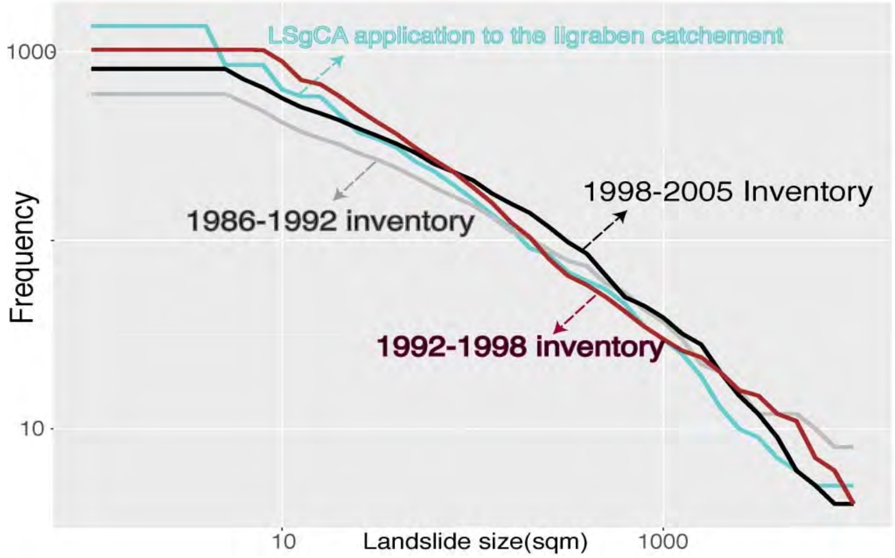


Fig. 2 Wider spaces of participation formats – local inhabitants' perspective

# Landslide risk model in Alpine context

- Cellular Automaton for landslide initiation and propagation tested in simulated fractal topographies & retrieves the same power law scaling as literature
- Application to Alpine context with frequency-size distribution refined for hazard



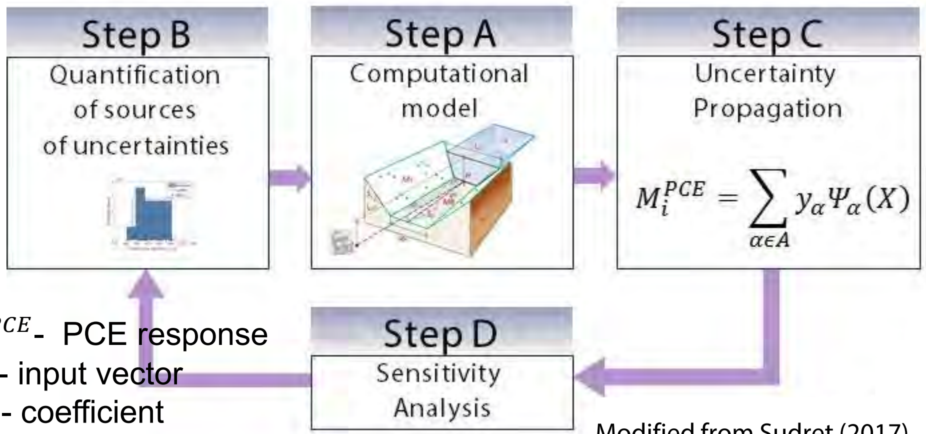


Jafarimanesh et al., Origin of the power-law exponent in the landslide frequency-size distribution, in revision

Jafarimanesh et al., Application to the Swiss Alps of the Landslide Generic Cellular Automaton, in prep.

# Uncertainty Quantification(UQ) in the Modeling of Dam-Break Consequences

- **Metamodeling** for **UQ and sensitivity analysis** of consequences of the potential **failure of a hydropower dam**, with particular focus on **relevant Swiss conditions;**

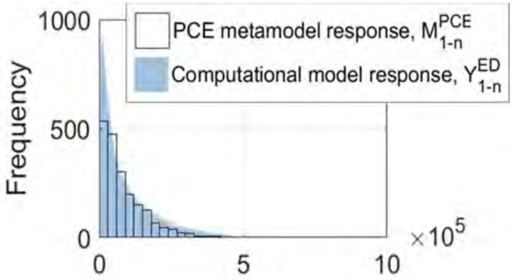


$$M_i^{PCE} = \sum_{\alpha \epsilon A} y_\alpha \Psi_\alpha(X)$$

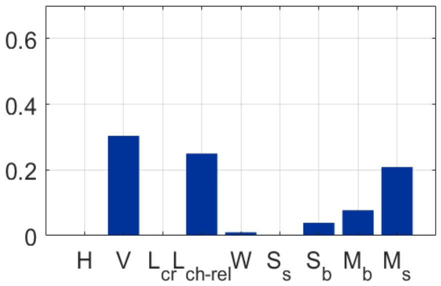
$M_i^{PCE}$- PCE response
$X_i$ - input vector
$y_\alpha$ - coefficient
$\Psi_\alpha$ - polynomials

Modified from Sudret (2017)

- **The metamodel** of the computational model was built using the **polynomial chaos expansion (PCE) technique** on the experimental design of only **2,000 sample points**;
- **$10^6$ realizations** of the **PCE metamodel** helped to build distributions describing the **variability of the model outputs** (see below examples for the peak discharge, $Q_{peak}$);
- **No additional sampling** was required to calculate **Sobol' sensitivity indices**.



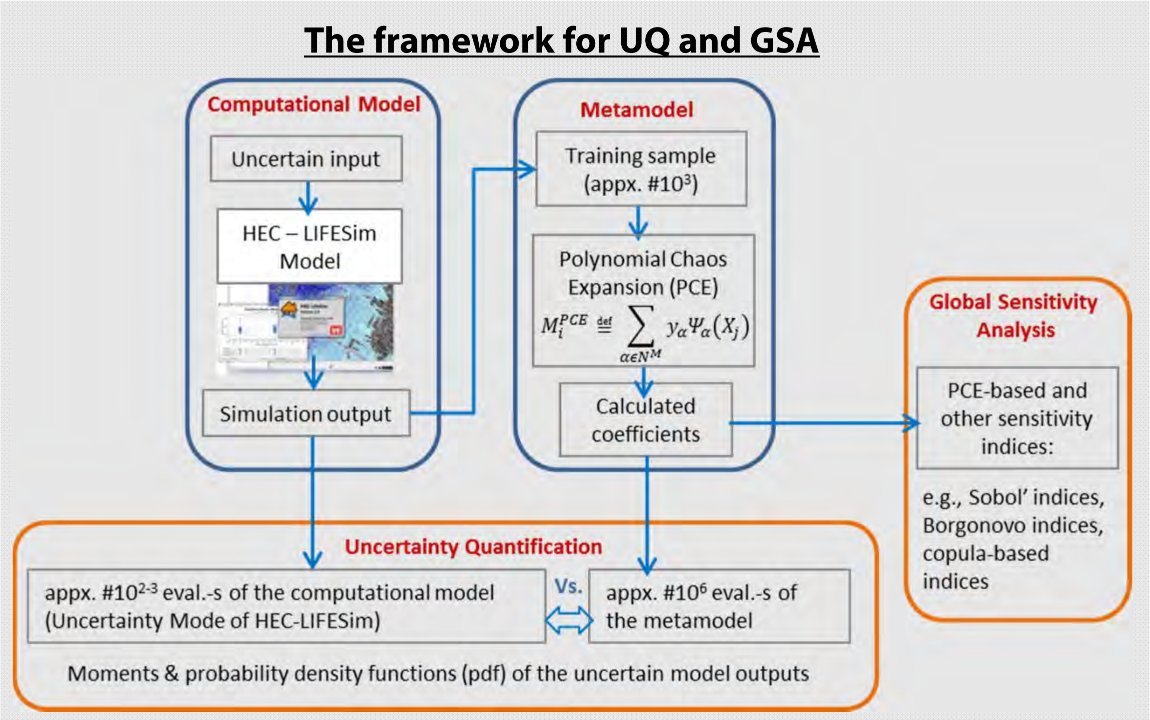
Computational, $Y_{i-n}^{ED}$, and PCE meta model response, $M_{1-n}^{PCE}$



First order Sobol' sensitivity indices

Kalinina et al. (in prep.)

# Quantitative Assessment of Uncertainties and Sensitivities in Life Loss estimates due to an Instantaneous Dam Break



**The framework for UQ and GSA**

**Computational Model**

Uncertain input

HEC – LIFESim Model

Simulation output

**Metamodel**

Training sample (appx. #$10^3$)

Polynomial Chaos Expansion (PCE)

$$M_i^{PCE} \overset{\text{def}}{=} \sum_{\alpha \in N^M} y_\alpha \Psi_\alpha(X_j)$$

Calculated coefficients

**Global Sensitivity Analysis**

PCE-based and other sensitivity indices:

e.g., Sobol’ indices, Borgonovo indices, copula-based indices

**Uncertainty Quantification**

appx. #$10^{2\text{-}3}$ eval.-s of the computational model (Uncertainty Mode of HEC-LIFESim)

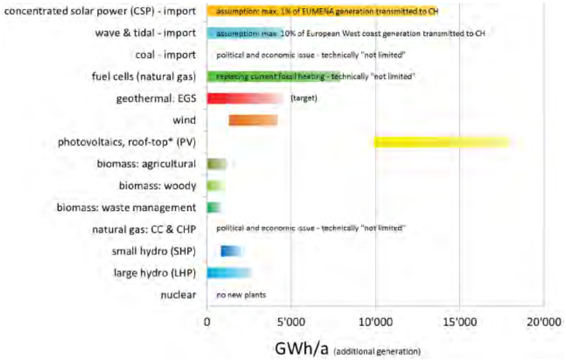
Vs.

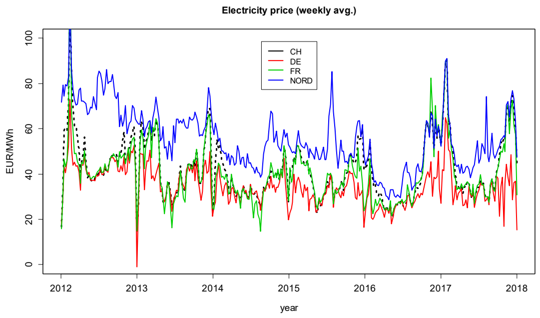
appx. #$10^6$ eval.-s of the metamodel

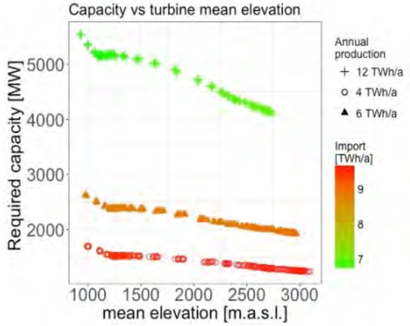
Moments & probability density functions (pdf) of the uncertain model outputs

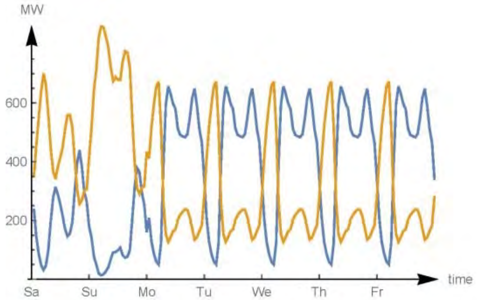
- **Adapt and integrate the HEC-LIFESim life-loss (LL) modeling tool with a metamodeling approach, including UQ and GSA.**
- **Application to a hypothetical, instantaneous dam break with conditions relevant for CH.**

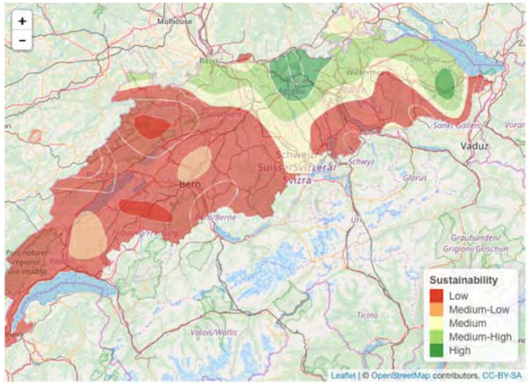
# T4.2 – Global Observatory of Electricity Resources

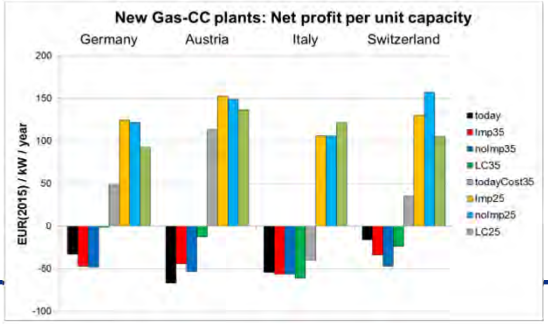


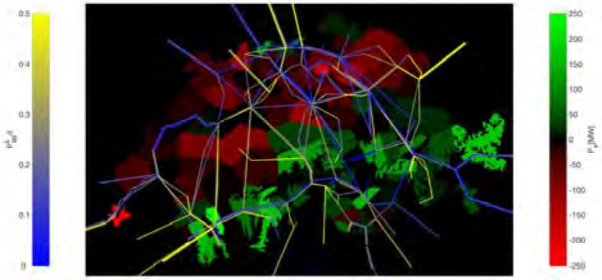






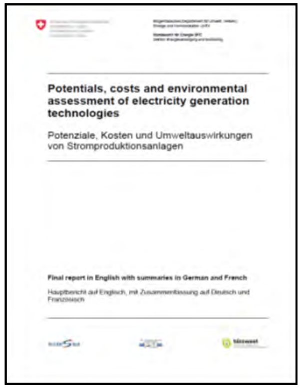






# Potential, Costs and Environmental Effects of Electricity Generation Technologies

- **Consistent evaluation of electricity generation technologies that are potentially relevant for Swiss supply until 2050**
- **Funded by** SFOE and SCCER SoE; **Additional contributions from** SCCER Biosweet
- **Report supports:** «Energieperspektiven 2017» and SFOE technology monitoring
- Final report including executive summary with technology "fact sheets".
  https://www.psi.ch/ta/PublicationTab/Final-Report-BFE-Project.pdf
- Synthesis Report: compact overview of results most important for CH.
  http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=en&name=en_854880113.pdf
- SCCER SoE Blog: "Can renewables fill the power gap?"



**Potentials, costs and environmental assessment of electricity generation technologies**

Potenziale, Kosten und Umweltauswirkungen von Stromproduktionsanlagen

**Final report in English with summaries in German and French**

Hauptbericht auf Englisch, mit Zusammenfassung auf Deutsch und Französisch

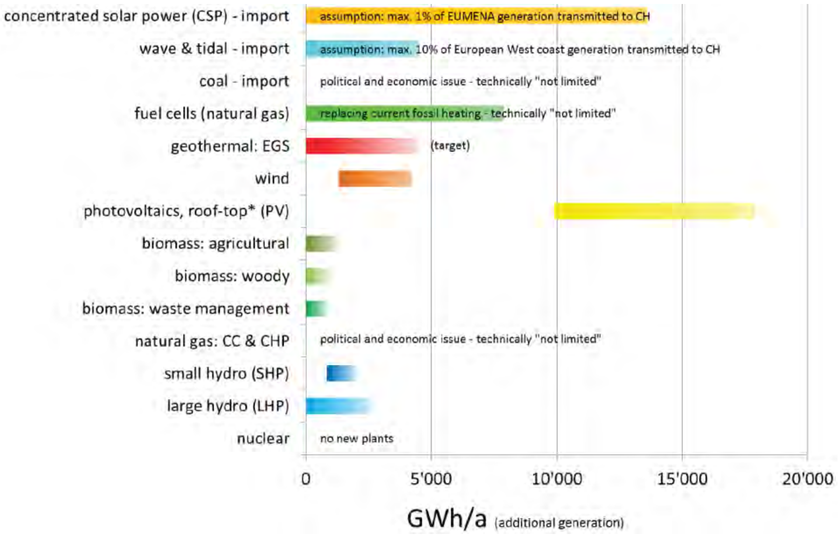
## Can renewables fill the power gap?

*April 2018 - by Christian Bauer*

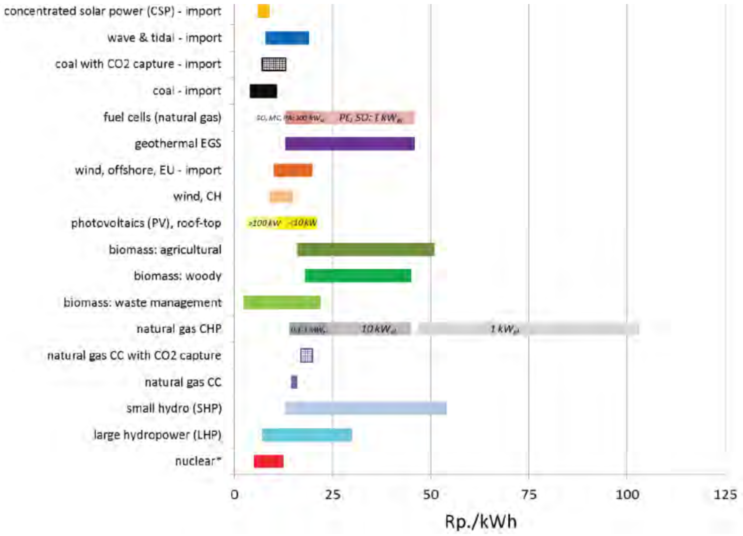
Sooner or later Switzerland must get by without nuclear power plants. This has been determined by the adoption of the Energy Strategy 2050. But how can the power gap be filled? Is there enough space and acceptance for photovoltaic installations and wind turbines in Switzerland, or will we have to import electricity from abroad? How much will the alternatives cost and what effects will they have on the environment? The Paul Scherrer Institute (PSI) has recently attempted to answer these and other questions for the Swiss Federal Office of Energy (SFOE).

# Potential, Costs and Environmental Effects of Electricity Generation Technologies

### Potentials for additional generation & supply



### LCOE in year 2050



Bauer et al. (2017)

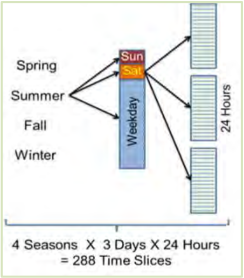
- **Key input to JA Scenario & Modeling for several modeling teams**
- **Update of current electricity generation costs (until Jan 2019)**
- **Similar analysis will be carried out for electricity storage technologies**

# Modeling Activities of Energy Economic Group (PSI)

## Elec. generation capacity

### European capacity expansion modeling

- Long-term capacity expansion in Europe under policy scenarios
- Scope: CH+ EU



## Electricity prices

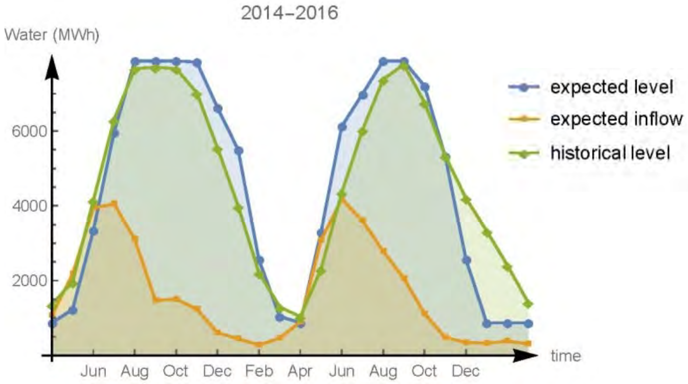
### Electricity market modeling

- Future wholesale price ranges under policy scenarios
- Scope: CH + surrounding countries

## Optimal profit against prices

### Hydropower stochastic dispatch modeling

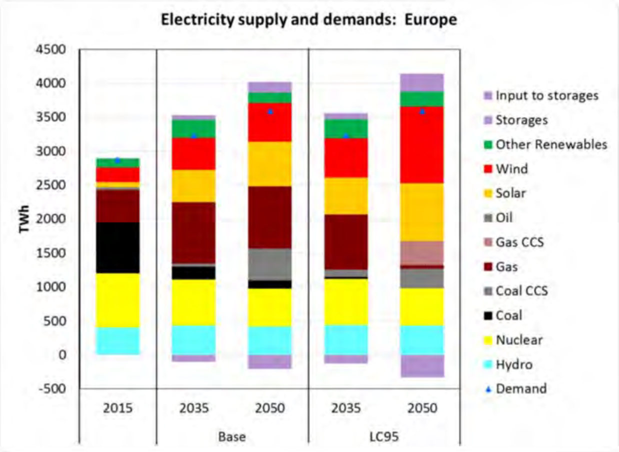
- Optimal production and pumping thresholds under exogenous prices
- Scope: Single utility



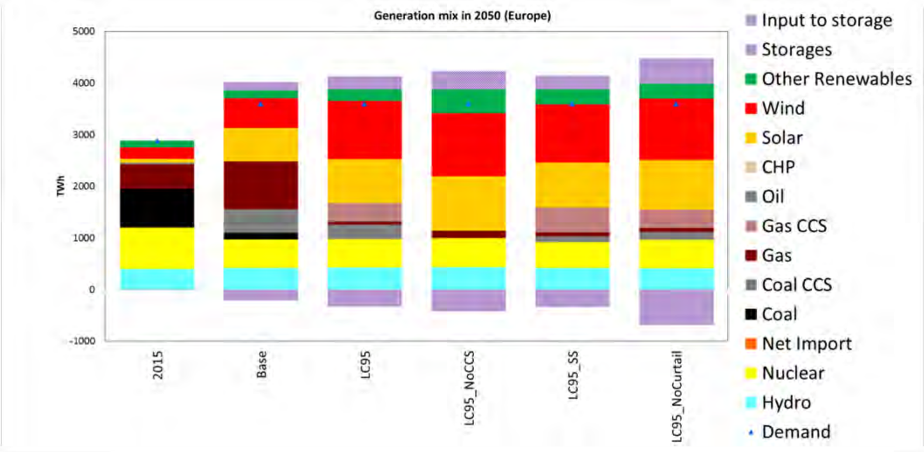
# EU production capacity expansion modeling

- **Multi region, cost-optimization model of electricity system of Europe: Long time horizon (2050), hourly time resolution (typical days)**
- **Near-term EU energy polices implemented (with new electricity storage options)**

**Electricity supply in 2015, 2035, and 2050**



**Electricity supply 2050 across scenarios**



- **Gas power** becomes transitional technology in short-/mid-term
- **Baseline scenario:** EU polices reduce power sector's $CO_2$ emission in 2050 by 60% (w.r.t. 2010)
- **Further decarbonization** requires high share of renewable ( > 40% of generation) and gas-based CCS technology. In 2050, the new renewables require 250-450 TWh (=5-10% of electricity load) shifted daily by **storage with 125-355 GW capacity**

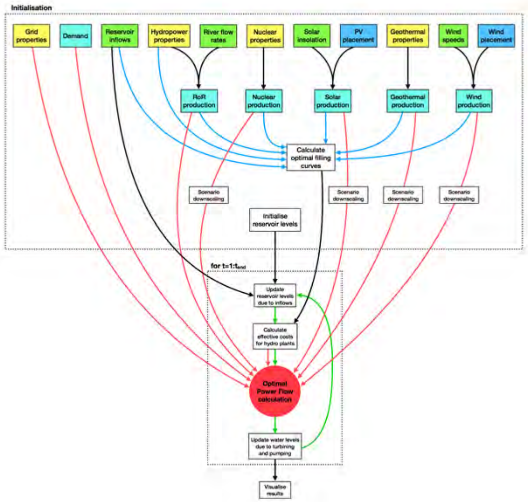
# Fully Renewable Swiss Power System

## Inputs:

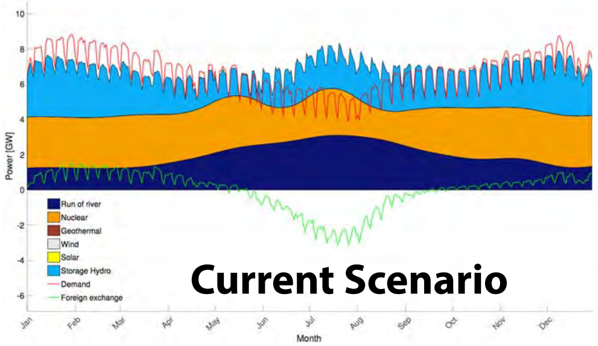
**Strategic Grid 2025**

**Renewable Placement**

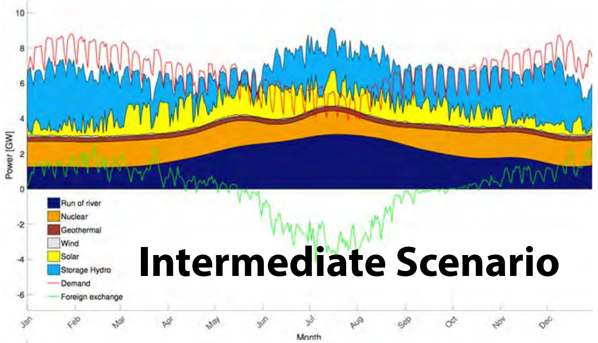
## Algorithm: Match Supply and Demand



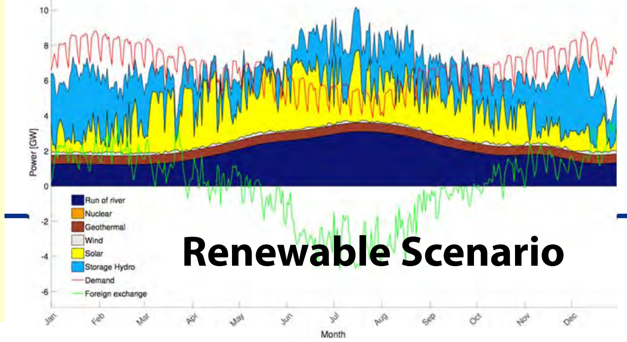
## Results: Generation and Demand



**Current Scenario**



**Intermediate Scenario**

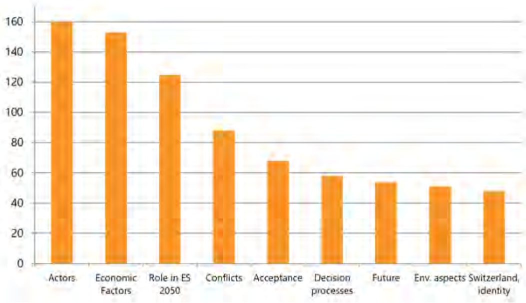


**Renewable Scenario**

Bartlett et al. (2018

- **Switzerland has the resources to be fully renewable.**
- **Transmission grid may be similarly or less stressed with increasing renewable penetration.**
- **Large scale foreign exchange or significant new storage facilities would be required.**
- **Alpine solar and wind resources could play a significant role in a future renewable Switzerland.**

# T4.3 – Socio-Economic-Political Drivers



**Project Development and Public Engagement Guideline**

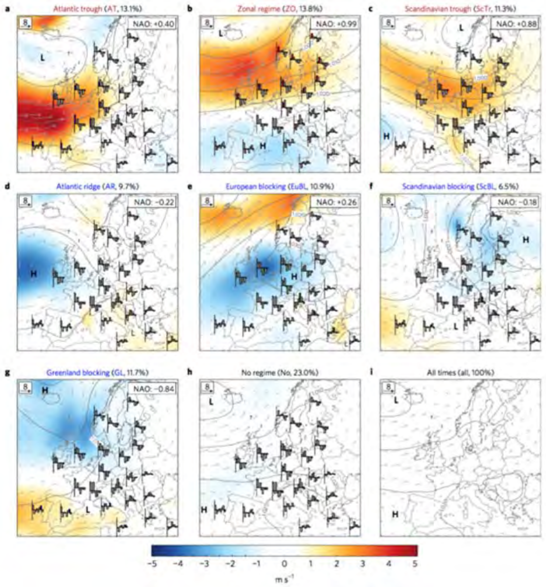
**Legal Context, Risk & Acceptability**

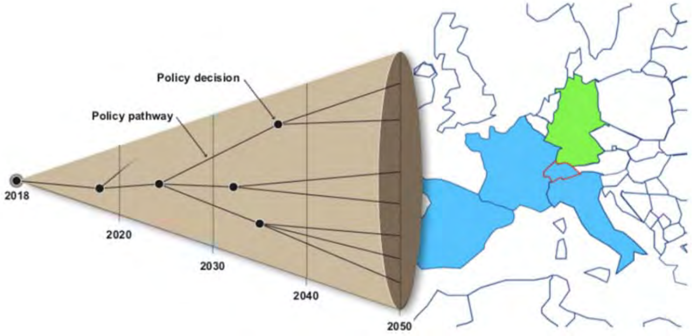
**WS1**

**WS2**

**Insights on Sources of Acceptability**

**Jointly Selected SoE P + D Projects**





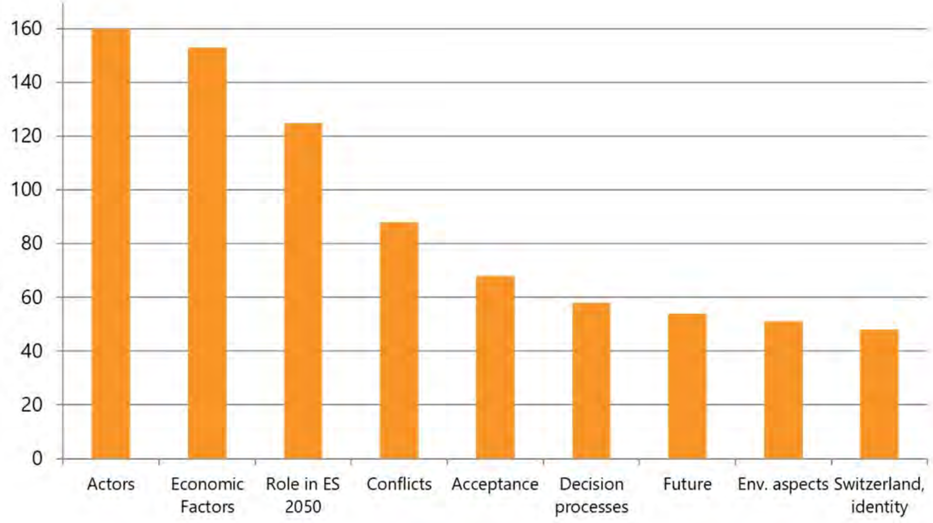
# Framing HP in Swiss Newspapers

- Media analysis in collaboration with ZHAW
- Complementing media analysis on DGE
- Providing a basis to test impacts of media frames on public acceptance
- Analysis completed

**First results**

- Predominantly framed as an economic issue
- Main actors are operators and federal offices
- Technical risk and periglacial dams are non issues

Most frequent topics in relationship to HP (n=170)



# Cantonal views on challenges to HP

- Collaboration with Uni Basel
- Assess the challenges encountered by cantons to expand HP
- Qualitative interviews with 9 Cantonal officers in charge of HP (covering 83% of Swiss HP production
- Qualitative content analysis
- Analysis ongoing

**First results**

- Goal conflicts between BFE and BAFU appears as the most limiting factor for HP
- Economic issues are perceived as conjunctural
- Cantons have little to no leverage to plan for HP
- They do not see wider public engagement as necessary. Information is enough
- Increasing discussions with operators about maintenance and safety costs.

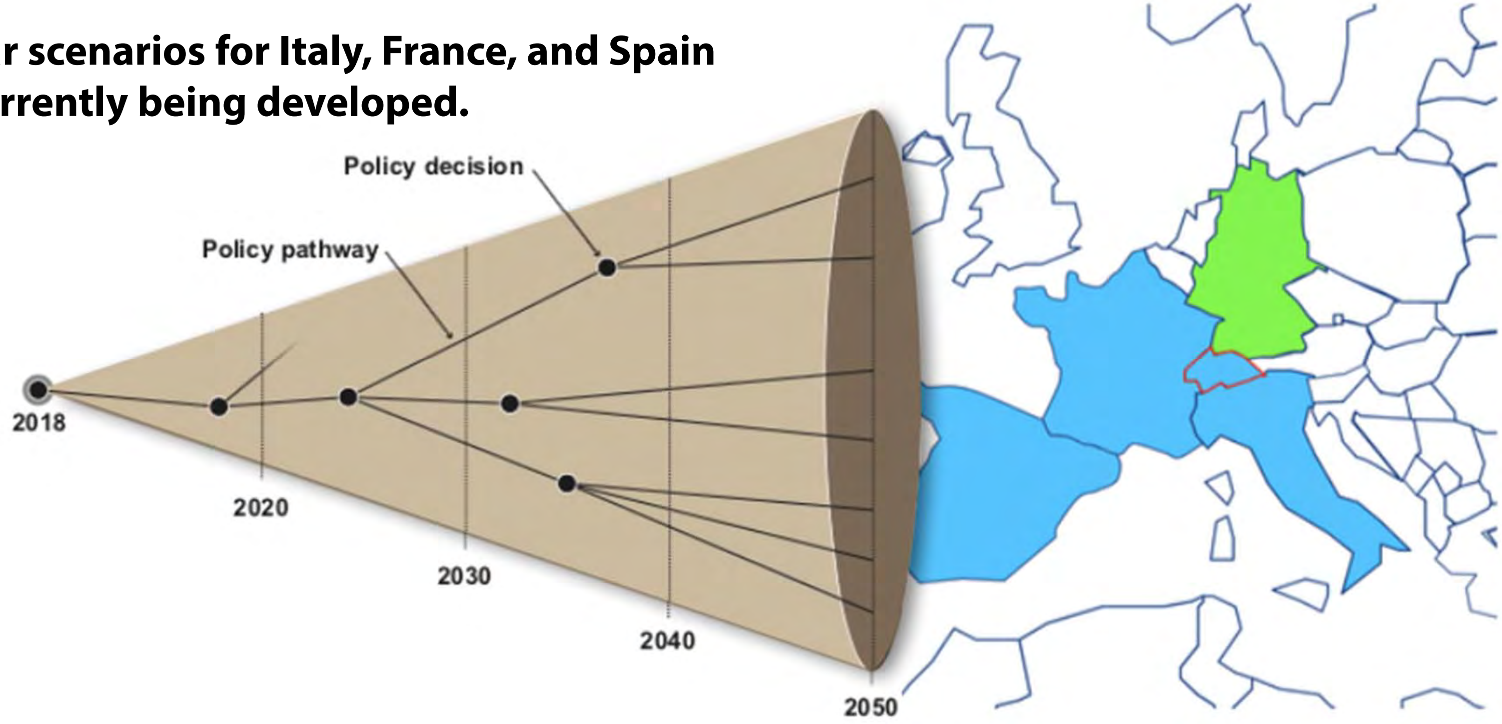
# Case study Lago Bianco

**Case study to assess stakeholder engagement during the concessioning process of the Lago Bianco pump-storage dam**

- Collaboration with University of Geneva (not JA CREST partner)
- Social network analysis (SNA) to assess nature of relationships of actors involved in the participatory process that led to the re-design of the project
- SNA completed with qualitative interviewing to identify the type of resources (legal, financial, expertise, legitimacy, social capital…) used by actors to assert their position
- Data collection is currently ongoing.

# Policy Pathways

- **The Climate Policy group at ETH is analysing the value of the flexibility that hydropower provides, as this depends on the policy pathways in neighbouring and nearby countries.**
- **So far, they have developed representative scenarios for Germany, based on literature review and stakeholder interviews.**
- **Similar scenarios for Italy, France, and Spain are currently being developed.**



# WP4 – Poster Pitches

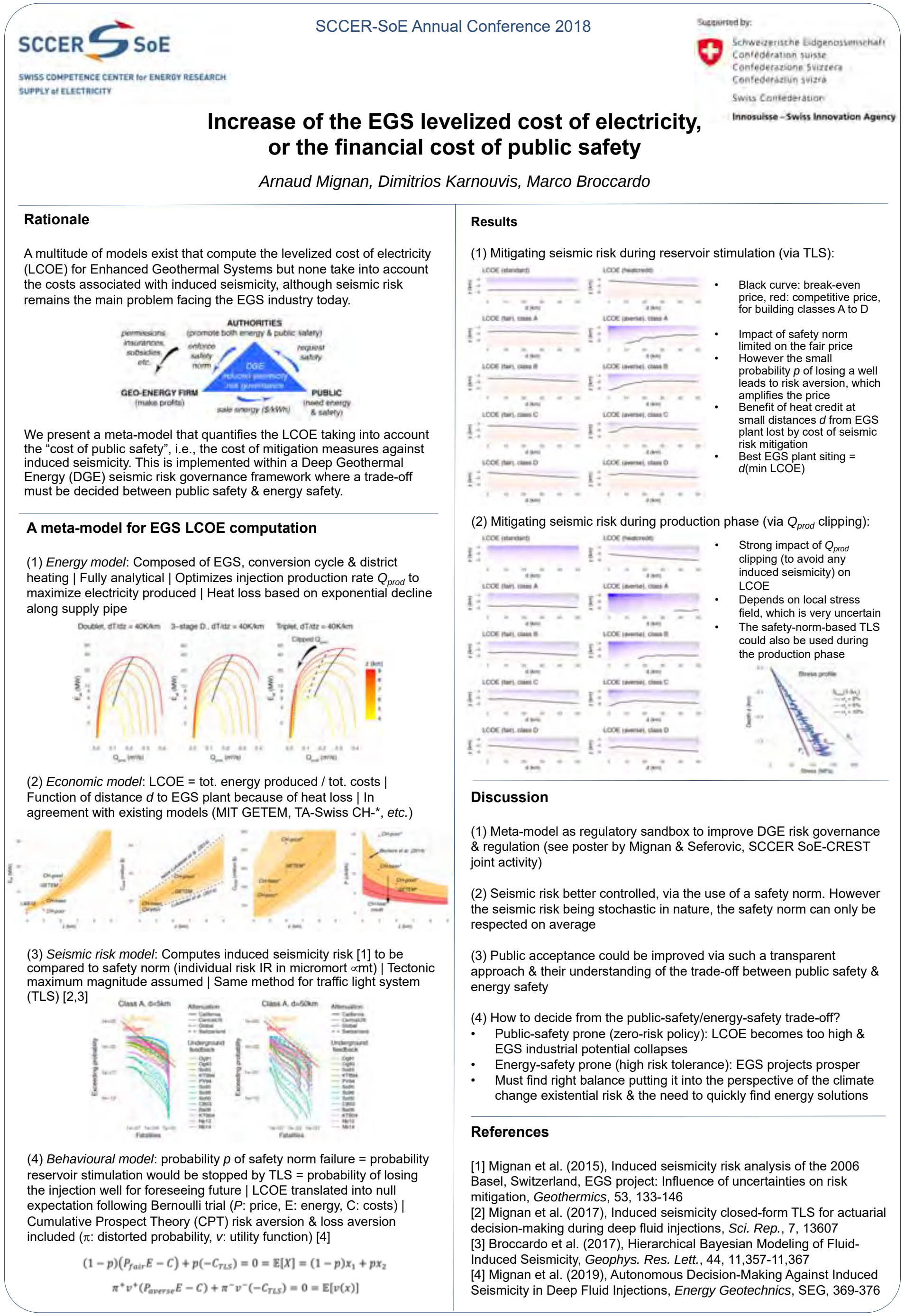
1. **Arnaud Mignan (ETHZ): Increase of the EGS levelized cost of electricity, or the financial cost of public safety**
2. **Matteo Spada (PSI); A preliminary sustainability analysis of potential areas for deep geothermal energy (DGE) systems: Application to Switzerland**
3. **Michael Lehning (WSL/EPFL): Heterogenity of Swiss environmental condition and its possible impact on the electrical system**

**→ WP4 has a total of 31 posters**

# What is the price of electricity produced by EGS plants?

- Economic models give price/kWh
- None consider the cost of seismic risk mitigation measures
- Seismic risk is the greatest problem that the EGS industry is facing

- **“Increase of the EGS LCOE, or the financial cost of public safety”**
    - DGE risk governance framework
    - Meta-model (electricity + heat production, economic model, seismic risk model, behavioural model, safety-norm-based TLS)
    - LCOE as main metric



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## Increase of the EGS levelized cost of electricity, or the financial cost of public safety

*Arnaud Mignan, Dimitrios Karnouvis, Marco Broccardo*

**Rationale**

A multitude of models exist that compute the levelized cost of electricity (LCOE) for Enhanced Geothermal Systems but none take into account the costs associated with induced seismicity, although seismic risk remains the main problem facing the EGS industry today.

We present a meta-model that quantifies the LCOE taking into account the “cost of public safety”, i.e., the cost of mitigation measures against induced seismicity. This is implemented within a Deep Geothermal Energy (DGE) seismic risk governance framework where a trade-off must be decided between public safety & energy safety.

**A meta-model for EGS LCOE computation**

(1) *Energy model*: Composed of EGS, conversion cycle & district heating | Fully analytical | Optimizes injection production rate $Q_{prod}$ to maximize electricity produced | Heat loss based on exponential decline along supply pipe

(2) *Economic model*: LCOE = tot. energy produced / tot. costs | Function of distance *d* to EGS plant because of heat loss | In agreement with existing models (MIT GETEM, TA-Swiss CH-*, *etc.*)

(3) *Seismic risk model*: Computes induced seismicity risk [1] to be compared to safety norm (individual risk IR in micromort ∝mt) | Tectonic maximum magnitude assumed | Same method for traffic light system (TLS) [2,3]

(4) *Behavioural model*: probability *p* of safety norm failure = probability reservoir stimulation would be stopped by TLS = probability of losing the injection well for foreseeing future | LCOE translated into null expectation following Bernoulli trial (*P*: price, E: energy, C: costs) | Cumulative Prospect Theory (CPT) risk aversion & loss aversion included (π: distorted probability, *v*: utility function) [4]

$$(1-p)(P_{fair}E-C)+p(-C_{TLS})=0=\mathbb{E}[X]=(1-p)x_1+px_2$$

$$\pi^+v^+(P_{averse}E-C)+\pi^-v^-(-C_{TLS})=0=\mathbb{E}[v(x)]$$

**Results**

(1) Mitigating seismic risk during reservoir stimulation (via TLS):

- Black curve: break-even price, red: competitive price, for building classes A to D
- Impact of safety norm limited on the fair price
- However the small probability *p* of losing a well leads to risk aversion, which amplifies the price
- Benefit of heat credit at small distances *d* from EGS plant lost by cost of seismic risk mitigation
- Best EGS plant siting = *d*(min LCOE)

(2) Mitigating seismic risk during production phase (via $Q_{prod}$ clipping):

- Strong impact of $Q_{prod}$ clipping (to avoid any induced seismicity) on LCOE
- Depends on local stress field, which is very uncertain
- The safety-norm-based TLS could also be used during the production phase

**Discussion**

(1) Meta-model as regulatory sandbox to improve DGE risk governance & regulation (see poster by Mignan & Seferovic, SCCER SoE-CREST joint activity)

(2) Seismic risk better controlled, via the use of a safety norm. However the seismic risk being stochastic in nature, the safety norm can only be respected on average

(3) Public acceptance could be improved via such a transparent approach & their understanding of the trade-off between public safety & energy safety

(4) How to decide from the public-safety/energy-safety trade-off?

- Public-safety prone (zero-risk policy): LCOE becomes too high & EGS industrial potential collapses
- Energy-safety prone (high risk tolerance): EGS projects prosper
- Must find right balance putting it into the perspective of the climate change existential risk & the need to quickly find energy solutions

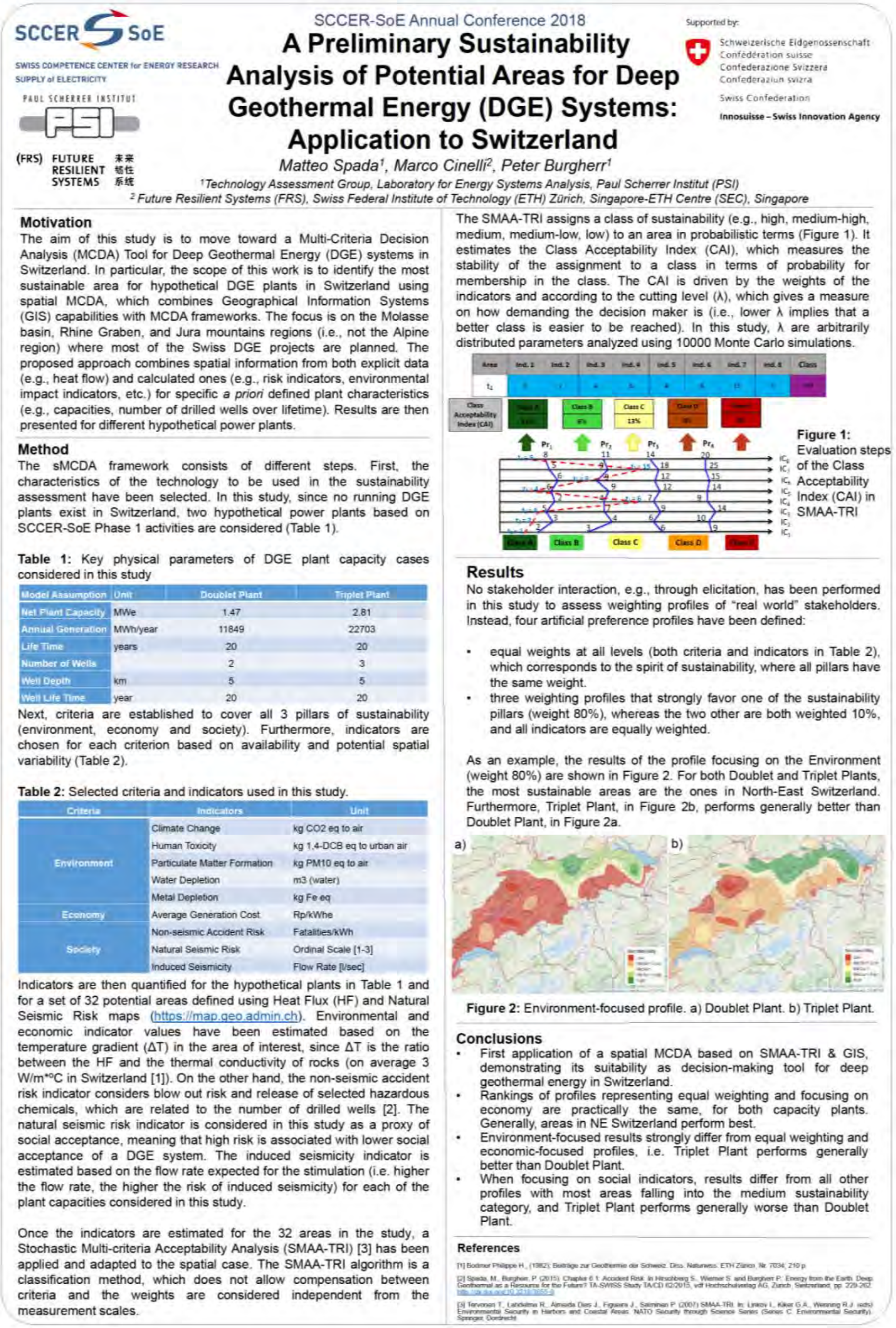
**References**

[1] Mignan et al. (2015), Induced seismicity risk analysis of the 2006 Basel, Switzerland, EGS project: Influence of uncertainties on risk mitigation, *Geothermics*, 53, 133-146
[2] Mignan et al. (2017), Induced seismicity closed-form TLS for actuarial decision-making during deep fluid injections, *Sci. Rep.*, 7, 13607
[3] Broccardo et al. (2017), Hierarchical Bayesian Modeling of Fluid-Induced Seismicity, *Geophys. Res. Lett.*, 44, 11,357-11,367
[4] Mignan et al. (2019), Autonomous Decision-Making Against Induced Seismicity in Deep Fluid Injections, *Energy Geotechnics*, SEG, 369-376

Futu

# Which are the most sustainable areas for DGE in Switzerland?

- Previous sustainability assessments of new renewables in Switzerland did not consider the spatial variability of criteria (e.g. economic, environmental and social).
- However, it is of great importance for DGE.
- "**A Preliminary Sustainability Analysis of Potential Areas for DGE Application to Switzerland**"
  - Spatial Multi-Criteria Decision Analysis (sMCDA) framework
  - Stochastic classification to rank 32 areas based on 11 indicators for 2 hypothetical types of DGE plants in Switzerland.
  - Different weighting profiles can influence performance of both plant type and area.



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## A Preliminary Sustainability Analysis of Potential Areas for Deep Geothermal Energy (DGE) Systems: Application to Switzerland

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### Motivation

The aim of this study is to move toward a Multi-Criteria Decision Analysis (MCDA) Tool for Deep Geothermal Energy (DGE) systems in Switzerland. In particular, the scope of this work is to identify the most sustainable area for hypothetical DGE plants in Switzerland using spatial MCDA, which combines Geographical Information Systems (GIS) capabilities with MCDA frameworks. The focus is on the Molasse basin, Rhine Graben, and Jura mountains regions (i.e., not the Alpine region) where most of the Swiss DGE projects are planned. The proposed approach combines spatial information from both explicit data (e.g., heat flow) and calculated ones (e.g., risk indicators, environmental impact indicators, etc.) for specific *a priori* defined plant characteristics (e.g., capacities, number of drilled wells over lifetime). Results are then presented for different hypothetical power plants.

### Method

The sMCDA framework consists of different steps. First, the characteristics of the technology to be used in the sustainability assessment have been selected. In this study, since no running DGE plants exist in Switzerland, two hypothetical power plants based on SCCER-SoE Phase 1 activities are considered (Table 1).

**Table 1:** Key physical parameters of DGE plant capacity cases considered in this study

| Model Assumption | Unit | Doublet Plant | Triplet Plant |
|---|---|---|---|
| Net Plant Capacity | MWe | 1.47 | 2.81 |
| Annual Generation | MWh/year | 11849 | 22703 |
| Life Time | years | 20 | 20 |
| Number of Wells | | 2 | 3 |
| Well Depth | km | 5 | 5 |
| Well Life Time | year | 20 | 20 |

Next, criteria are established to cover all 3 pillars of sustainability (environment, economy and society). Furthermore, indicators are chosen for each criterion based on availability and potential spatial variability (Table 2).

**Table 2:** Selected criteria and indicators used in this study.

| Criteria | Indicators | Unit |
|---|---|---|
| Environment | Climate Change | kg CO2 eq to air |
| | Human Toxicity | kg 1,4-DCB eq to urban air |
| | Particulate Matter Formation | kg PM10 eq to air |
| | Water Depletion | m3 (water) |
| | Metal Depletion | kg Fe eq |
| Economy | Average Generation Cost | Rp/kWhe |
| Society | Non-seismic Accident Risk | Fatalities/kWh |
| | Natural Seismic Risk | Ordinal Scale [1-3] |
| | Induced Seismicity | Flow Rate [l/sec] |

Indicators are then quantified for the hypothetical plants in Table 1 and for a set of 32 potential areas defined using Heat Flux (HF) and Natural Seismic Risk maps (https://map.geo.admin.ch). Environmental and economic indicator values have been estimated based on the temperature gradient ($\Delta T$) in the area of interest, since $\Delta T$ is the ratio between the HF and the thermal conductivity of rocks (on average 3 W/m*°C in Switzerland [1]). On the other hand, the non-seismic accident risk indicator considers blow out risk and release of selected hazardous chemicals, which are related to the number of drilled wells [2]. The natural seismic risk indicator is considered in this study as a proxy of social acceptance, meaning that high risk is associated with lower social acceptance of a DGE system. The induced seismicity indicator is estimated based on the flow rate expected for the stimulation (i.e. higher the flow rate, the higher the risk of induced seismicity) for each of the plant capacities considered in this study.

Once the indicators are estimated for the 32 areas in the study, a Stochastic Multi-criteria Acceptability Analysis (SMAA-TRI) [3] has been applied and adapted to the spatial case. The SMAA-TRI algorithm is a classification method, which does not allow compensation between criteria and the weights are considered independent from the measurement scales.

The SMAA-TRI assigns a class of sustainability (e.g., high, medium-high, medium, medium-low, low) to an area in probabilistic terms (Figure 1). It estimates the Class Acceptability Index (CAI), which measures the stability of the assignment to a class in terms of probability for membership in the class. The CAI is driven by the weights of the indicators and according to the cutting level ($\lambda$), which gives a measure on how demanding the decision maker is (i.e., lower $\lambda$ implies that a better class is easier to be reached). In this study, $\lambda$ are arbitrarily distributed parameters analyzed using 10000 Monte Carlo simulations.

**Figure 1:** Evaluation steps of the Class Acceptability Index (CAI) in SMAA-TRI

### Results

No stakeholder interaction, e.g., through elicitation, has been performed in this study to assess weighting profiles of "real world" stakeholders. Instead, four artificial preference profiles have been defined:

- equal weights at all levels (both criteria and indicators in Table 2), which corresponds to the spirit of sustainability, where all pillars have the same weight.
- three weighting profiles that strongly favor one of the sustainability pillars (weight 80%), whereas the two other are both weighted 10%, and all indicators are equally weighted.

As an example, the results of the profile focusing on the Environment (weight 80%) are shown in Figure 2. For both Doublet and Triplet Plants, the most sustainable areas are the ones in North-East Switzerland. Furthermore, Triplet Plant, in Figure 2b, performs generally better than Doublet Plant, in Figure 2a.

**Figure 2:** Environment-focused profile. a) Doublet Plant. b) Triplet Plant.

### Conclusions

- First application of a spatial MCDA based on SMAA-TRI & GIS, demonstrating its suitability as decision-making tool for deep geothermal energy in Switzerland.
- Rankings of profiles representing equal weighting and focusing on economy are practically the same, for both capacity plants. Generally, areas in NE Switzerland perform best.
- Environment-focused results strongly differ from equal weighting and economic-focused profiles, i.e. Triplet Plant performs generally better than Doublet Plant.
- When focusing on social indicators, results differ from all other profiles with most areas falling into the medium sustainability category, and Triplet Plant performs generally worse than Doublet Plant.

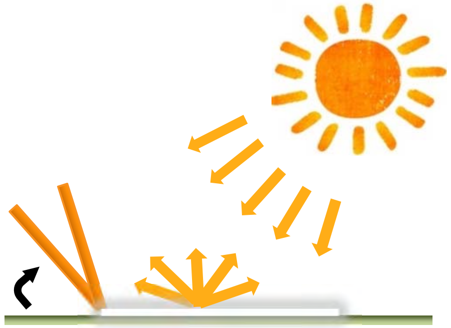
### References

[1] Bodmer Philippe H., (1982): Beiträge zur Geothermie der Schweiz. Diss. Naturwiss. ETH Zürich, Nr. 7034, 210 p.

[2] Spada, M., Burgherr, P. (2015). Chapter 6.1: Accident Risk. In Hirschberg S., Wiemer S. and Burgherr P.: Energy from the Earth. Deep Geothermal as a Resource for the Future? TA-SWISS Study TA/CD 62/2015, vdf Hochschulverlag AG, Zurich, Switzerland, pp. 229-262. http://dx.doi.org/10.3218/3655-8

[3] Tervonen T., Lahdelma R., Almeida Dias J., Figueira J., Salminen P. (2007) SMAA-TRI. In: Linkov I., Kiker G.A., Wenning R.J. (eds) Environmental Security in Harbors and Coastal Areas. NATO Security through Science Series (Series C: Environmental Security). Springer, Dordrecht

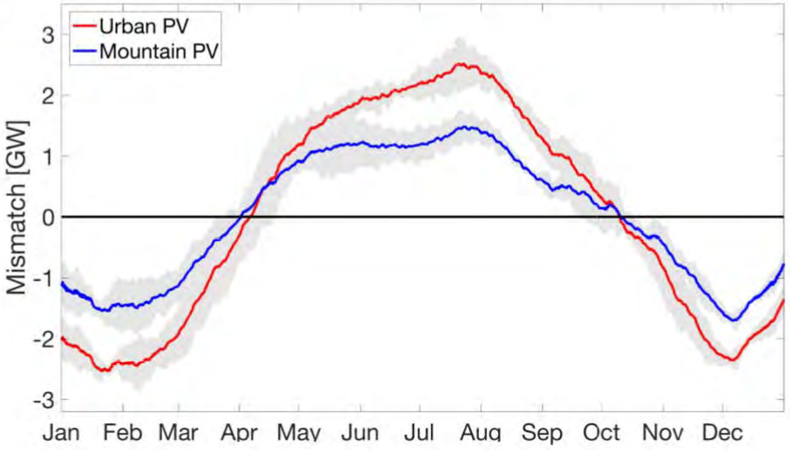
# How to Increase Winter PV Production

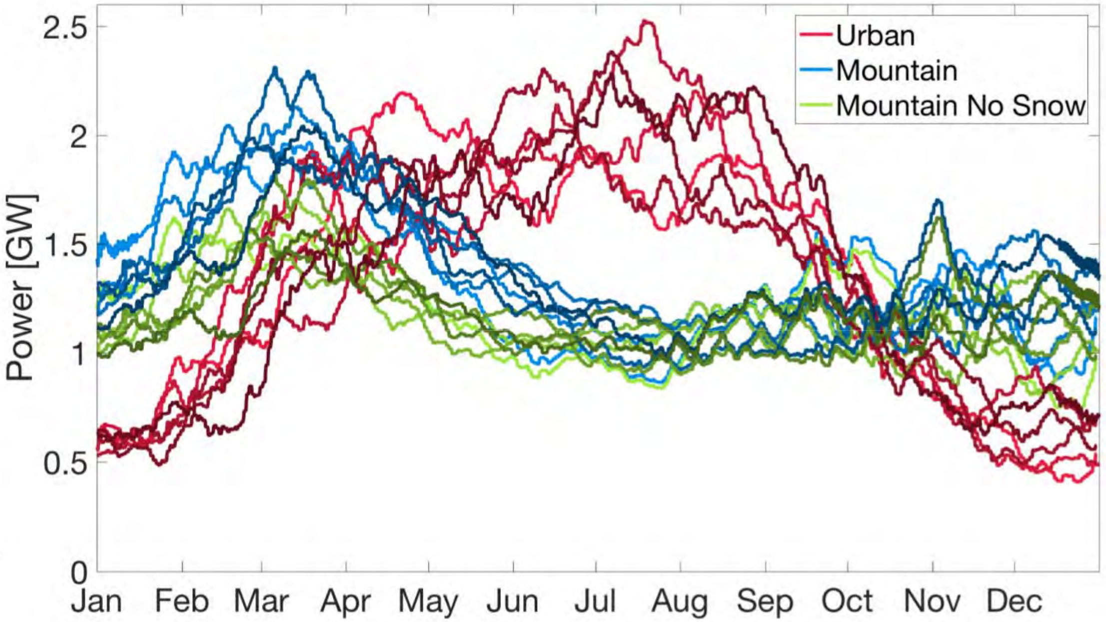


1. More radiation in winter

2. More ground reflection in winter

3. Steeper panel tilt





# ES2050: Required wind power capacity