Task 4.2

Title

Global observatory of electricity resources

Projects (presented on the following pages)

Modelling of dispatch of stored hydropower
Martin Densing

Electricity Prices Under Energy Policy Scenarios and Profitability of Hydropower
Martin Densing, Evangelos Panos

How will geothermal energy transform the environmental performance of Geneva's heating and cooling mix from a life-cycle perspective?
Astu Sam Pratiwi, Evelina Trutnevyte

A stochastic method for spatial Multi-Criteria Decision Analysis: Application to Deep Geothermal Energy in Switzerland
Matteo Spada, Marco Cinelli, Peter Burgherr

Energy system pathways with low environmental impacts and costs
Laurent Vandepaer, Panos Evangelos, Christian Bauer, Ben Amor

Nonlinear Inverse Demand Curves in Electricity Market Modeling
Yi Wan, Martin Densing

The potential & levelized cost of solar PV in Switzerland
Xiaojin Zhang, Christian Bauer

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Modelling of dispatch of stored hydropower

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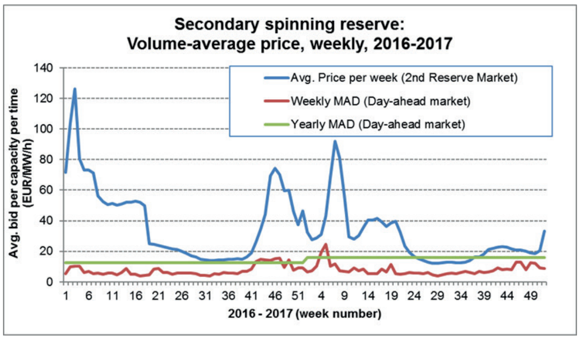
Motivation

- Traditional modeling of dispatch of stored energy, that is, when to release energy for generation and when to charge (e.g. in case of pumped-storage hydropower plants) faces **issues:** E.g., the **time horizon**: The dispatch decision is hourly (or sub-hourly), but the time horizon for price-driven dispatch is a year because of the seasonality of electricity prices and of natural water inflow. Moreover, several markets may investigated (ancillary services).
- **Model of a single plant vs. aggregated Swiss hydropower**: Commercial dispatch software is usually tuned to a specific set of plants. E.g., it is not well known how "academic" hydropower dispatch can approximate aggregated Swiss hydro storage.
- **Research directions:** ***(i)*** *Theoretical model of ancillary services;* ***(ii)*** *Change in optimal dispatch under price scenarios 2050;* ***(iii)*** *Model comparison for aggregated Swiss hydropower*
- Partners in (i) + (ii): **Karlsruhe Institute of Technology (KIT)** and **SFOE (Project *PowerDesign*) [1,2]**.
- Application of linear optimization model with exogenous stochastic prices, deterministic inflow, and reservoir constraints in expectation

I. Lower bound on secondary spinning reserve entry [1]

- A linear maximization problem has always an associated maximization problem (the "dual"). It can be shown: the dual yields necessary conditions to enter spinning reserve service: **Capacity payment (per time unit, per MW) >= Mean absolute deviation from the median (MAD) of electricity prices**.



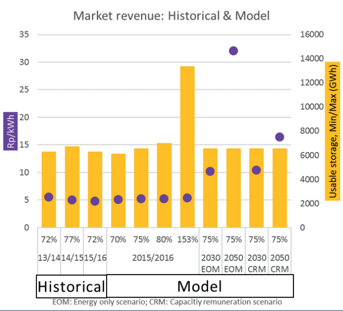
- Result: Price data of spinning reserve in Switzerland (Swissgrid, 2018) and MAD of power prices (EPEX, 2018) validate the analytically derived lower bound of spinning reserve price

II. Future scenarios of electricity prices: Profit & Cycling [2]

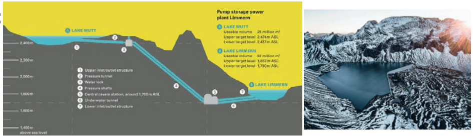
- Model input: Swiss power price scenarios, driven by large deployment of renewables in neighboring countries and CH, and calculated by **Karlsruhe Institute of Technology:** (i) **EOM 2050** ("energy-only-market"): has no market mitigation measures against price peaks (capacity scarcity); (ii) **CRM 2050** ("capacity remuneration mechanisms"): such measures are in place.

Validation and scenario analysis for the example of aggregated Swiss stored hydropower:

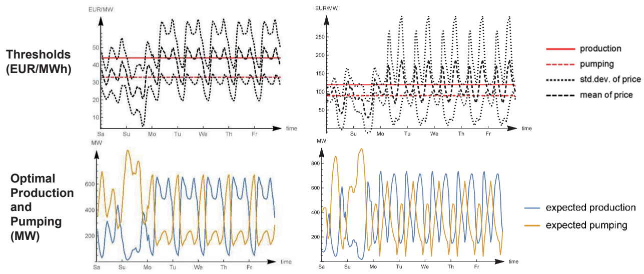
- Scenarios for 2050 (EOM and CRM) have high price levels
- → hydropower, as a price-taker, has higher profits.
- Storage volume in relation to today's generation capacity seems to be properly sized.



Example of **Muttsee:** 1GW pump-storage, ~0 natural inflow, large lower reservoir



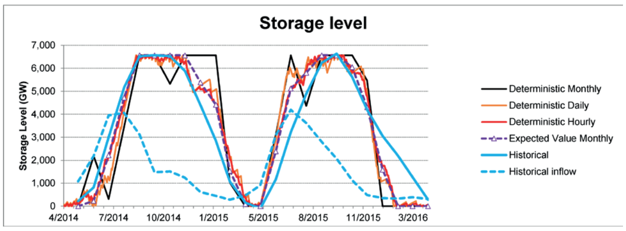
Price distribution of years 2015-16 | **Price distribution of 2050 Scenario: Energy-only-Market**



- Result: More volatile electricity prices having different patterns in the considered scenarios in 2050 leads to more cycling over a week → more turbine wear-down

III. Modelling Comparison [3]

- Example: **Aggregated Swiss stored hydropower** (pumps are neglected) over two years (Apr 2014 - Mar 2016). Input: electricity prices, natural inflow; output: storage levels, dispatch.
- **Comparison:** Models with *deterministic* prices (mean of prices), with different time steps: (i) monthly, (ii) daily, (iii) hourly; and (iv) monthly *stochastic* model with reservoir constraints in expectation



- Result: Monthly stochastic model can outperform monthly deterministic model. To keep in mind: The (many) plant owners of the 100+ different plants dispatch in reality by idiosyncratic rules.

Conclusions

- A stochastic model approach is presented based on the statistical properties of electricity prices. Based on this model, a first analytical treatment of spinning reserve provision can be provided.
- Because boundary conditions by the power markets will likely change for Swiss stored hydropower (e.g. see the 2050 scenario of dispatch above), we focus modeling of stochastics and seasonality.

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Electricity Prices Under Energy Policy Scenarios and Profitability of Hydropower

Martin Densing (martin.densing@psi.ch), Evangelos Panos
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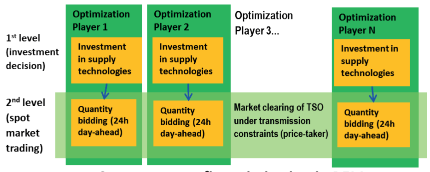
Within Task 4.2 "Global Observatory of Electricity Resources" the Energy Economics Group investigates:
1. *Price formation on the Swiss wholesale electricity markets* and long-term price development under energy policy scenarios of Switzerland and the EU. Emphasis is on a fundamental model of reasonable size and complexity that can approximate today's prices
2. *Hydropower dispatch optimization against electricity prices*. Emphasis is on models that take into account the probability distribution, but that are still numerical tractable for sensitivity analyses (hence no modeling with a scenario tree, which grows exponentially in time steps)
3. *Long-term investment and electricity dispatch for Switzerland and EU*

Scenario modeling with BEM – Cross-Border Electricity Market model

- Understanding price-formation and investments on electricity markets
- Day-ahead wholesale electricity prices (which are usually above marginal production costs) are calibrated by using a game-theoretic model of Switzerland and surrounding countries

Regions in BEM



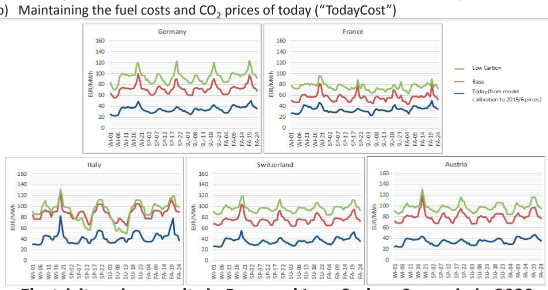
Concurrent profit optimization in BEM

Results for **two core scenarios** for year 2030 are presented:

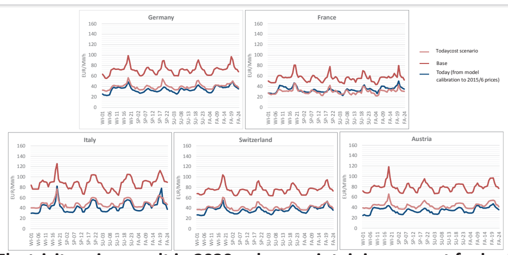
	Base	Low Carbon
Description	Reference scenario, based on EU TRENDS 2016 Scenario of EC	Climate scenario -40% reduction of CO_2 in 2030 from 1990 levels ("Clean Energy for All Europeans")
Fuel prices in 2030 (1)	Gas: 28 €/MWh, Coal: 12 €/MWh (in EUR_{2015})	
CO_2 price in 2030	30 €/tCO_2	80 €/tCO_2 (2)

[1] IEA World Energy Outlook 2017, New Policies Scenario [2] IEA World Energy Outlook 2017, Sustainable Scenario
Today's gas price (2015/6) 14 €/MWh, today's coal price 9 €/MWh

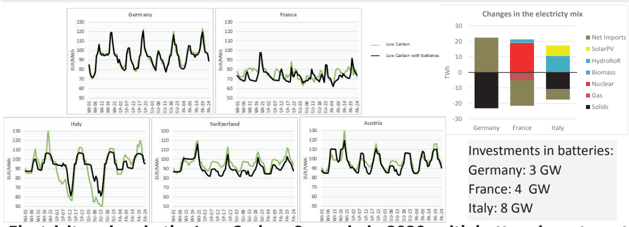
Two **additional variants**:
a) Enabling investment in batteries (transmission level) for additional flexibility
b) Maintaining the fuel costs and CO_2 prices of today ("TodayCost")



Electricity price results in Base and Low Carbon Scenario in 2030
→ Germany: Prices driven by CO_2 and gas prices (despite more PV+Wind)



Electricity price result in 2030, when maintaining current fuel prices
→ Electricity price increase key factors (in order of magnitude):
(1) Fossil fuel price, especially gas (indirectly CO_2 prices), (2) Load levels, (3) penetration of wind & solar, (4) decommissioning (mainly nuclear power)



Investments in batteries:
Germany: 3 GW
France: 4 GW
Italy: 8 GW

Electricity prices in the Low Carbon Scenario in 2030, with battery investments allowed
→ Additional (relatively small) storage can help to shave price-peaks

Hydropower Dispatch Modeling

Linear stochastic multi-period control model that optimizes expected profit under expected water constraints. Input: Price-distributions over time steps. Reduced example of a single-period model:

- Constraint on water-level in expectation
- $S \in L^1_+$ electricity spot price (EUR/MWh), continuous distribution function
- $u^\pm : \mathbb{R}_+ \to \mathbb{R}_+$ control function, $u^\pm(S)$: turbined/pumped water (MWh)
- Maximal capacity, available water per period: $u^+_{max} > I > 0$
- $\eta \in (0,1)$ efficiency of pumping

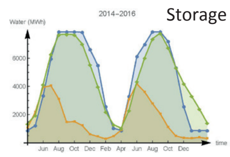
$$\max_{u^\pm} \mathbb{E}\left[Su^+(S) - \frac{1}{\eta} Su^-(S)\right]$$
$$\text{s.t.} \begin{cases} I - \mathbb{E}[u^+(S) - u^-(S)] \geq 0 \\ 0 \leq u^\pm(S) \leq u^\pm_{max} \end{cases}$$

Optimal solution:

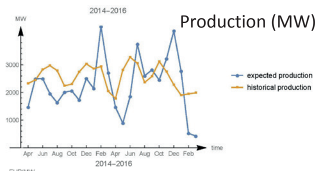
$$\hat{u}^+(S) = u^+_{max} 1_{\{S \geq \hat{q}\}}, \quad \hat{u}^-(S) = u^-_{max} 1_{\{S \leq \eta\hat{q}\}}, \quad \hat{q} \text{ given by}$$
$$u^+_{max}\mathbb{P}[S \geq \hat{q}] - u^-_{max}\mathbb{P}[S \leq \eta\hat{q}] = I$$

1. Example: Stored hydropower (Switzerland aggregated into 1 plant):

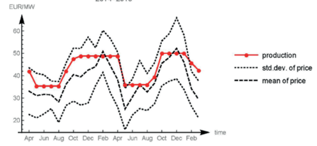
Storage (MWh)



Production (MW)

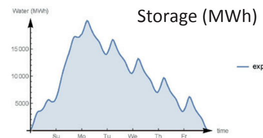


Production threshold, i.e. water value (EUR/MWh):

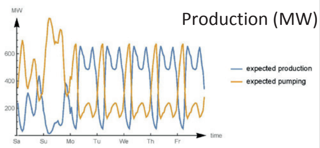


2. Example: 1 GW Pumped-storage over a week:

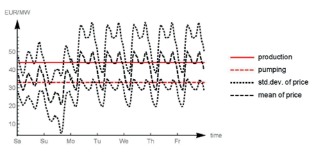
Storage (MWh)



Production (MW)

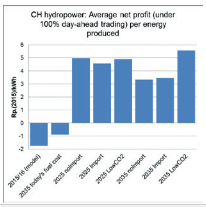


Production and pumping thresholds (EUR/MWh):



Hydropower Profitability by using scenario prices from BEM [3]

Swiss Hydropower is analyzed under different scenarios in target years 2025 and 2035: (i) Annual imports allowed (yes/now); (ii) Low carbon scenario (high CO_2 price of Swiss NEP scenario); today's fuel costs



- **Preliminary** results (VSE-PSEL project [3]):
  - Hydropower plants will not be profitable if today's fuel costs prevail (e.g. CO_2 price < 10 EUR/tCO2 in European ETS)
  - Hydropower can become more profitable under high gas (and CO_2) prices

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SCCER-SoE Annual Conference 2019: 3 & 4 September 2019

How will geothermal energy transform the environmental performance of Geneva's heating and cooling mix from a life-cycle perspective?

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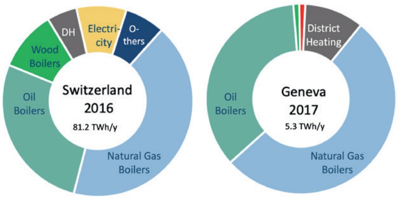


Figure 1. Heat delivery to buildings by source.
Adapted from Narula et al., 2019 and Quiquerez et al., 2020

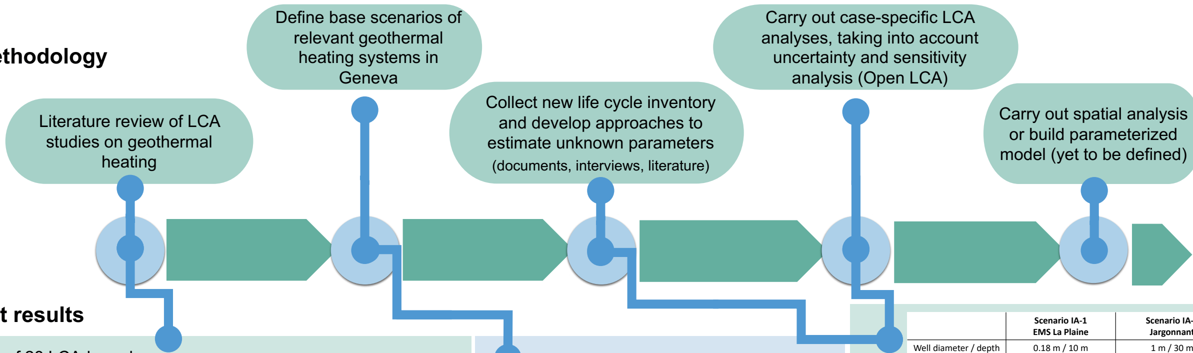
Background

- In Geneva, like Switzerland, fossil fuels dominate the heating sector [1] (Figure 1).
- A combination of geothermal heating applications in Geneva could potentially cover 75% of the heating demand by 2030 [2].
- GEothermie 2020 program [3] aims to comprehend Geneva's subsurface characteristics better and to develop new geothermal projects.
- The environmental impacts of geothermal energy inclusion in the heating and cooling mix need to be evaluated to ensure their sustainable deployment.
- Life Cycle Assessment (LCA), as an widely used component of sustainability assessments, is the suitable methodology to analyze the environmental performance of geothermal energy in the heating and cooling sector.

Research questions

1. How do different standalone geothermal heating and cooling systems perform environmentally in the context of the Canton of Geneva?
2. What are the key parameters that influence this performance and how this performance could be improved?
3. How could the deployment of geothermal heating and cooling change the environmental performance of the current heating and cooling mix in Geneva?

Methodology



First results

- Out of 28 LCA-based studies on geothermal heating systems in the literature, 20 cover Ground Source Heat Pump (GSHP).
- A comparison between LCA studies and existing installations shows a lack of LCA studies on medium-enthalpy geothermal systems involving extraction of groundwater, despite their popular deployment in Europe (Figure 2).
- The impacts of GSHP depend on the electricity mix and COP [4-6], thus have a large spread and are not always better than individual oil boilers (Figure 3).
- Groundwater systems are reported to perform relatively better than oil boilers (Figure 3).

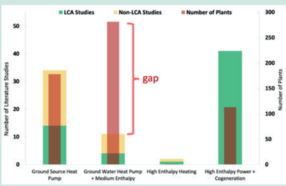


Figure 2. Identified research gap in LCA for open the geothermal systems

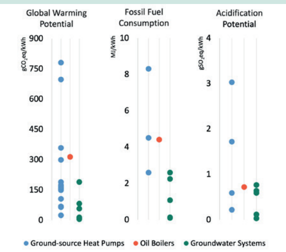


Figure 3. Summary of the reported impacts in the literature and the comparison to the impacts of individual oil boilers (except for GWP, only CML-based calculations are plotted)

- LCA on groundwater geothermal systems is needed to strengthen the literature, as well as to support GEothermie 2020 program.

	HP INDIVIDUAL OR DECENTRALIZED (A) La Plaine, Jargonnant		HP + DISTRICT HEATING (B) Concorde	NO HP + DISTRICT HEATING (C) Versoix, Rive Gauche	
	Scenario IA-1 (*EMS La Plaine)	Scenario IA-2 (*Jargonnant)	Scenario IB		SMALL DEPTH (I) < 100 m Versoix, Concorde
	Scenario IIA		Scenario IIB	Scenario IIC	MEDIUM DEPTH (II) < 1500 m Satigny, Bassersdorf, Lavey-le-Bains
			Scenario IIIB	Scenario IIIC	LARGE DEPTH (III) >1500 Rittershoffen (FR), Riehen, Thônex

***Table 1.** Scenarios of groundwater extraction geothermal systems that could be relevant in Geneva and their installation references. *The case studies analyzed so far are presented in the next section.*

- Several scenarios are defined to represent the probable configurations of subsurface and surface systems in Geneva (Table 1).
- Existing installations (written in green in Table 1) are the identified references to collect life cycle inventory, to develop LCA models, and to validate the models.

- LCA studies were carried out for EMS La Plaine (Scenario IA-1) and Jargonnant (Scenario IA-2) for a lifetime of 30 years. Table 2 presents the differences between the two.
- Operation stage is the major contributor to almost all environmental impacts (Figure 4).
- Compared to oil boilers, the two systems have lower climate change impact, emit less particulate matter, and depend less on fossil fuel (Figure 5).

	Scenario IA-1 EMS La Plaine	Scenario IA-2 Jargonnant
Well diameter / depth	0.18 m / 10 m	1 m / 30 m
Flowrate	5.5 l/s	30 l/s
Cooling	Passive	Active
Solar Thermal	Yes	No

***Table 2.** Main differences between Scenario IA-1and IA-2*

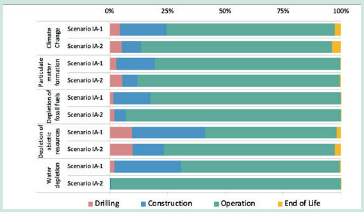


***Figure 4.** Preliminary results on the contribution of different life-cycle stages of Scenario IA-1 and Scenario IA-2 towards five selected environmental impacts*

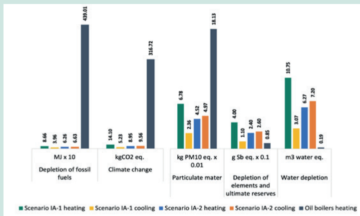


***Figure 5.** Preliminary results on environmental impacts by Scenario IA-1 and Scenario IA-2 as compared to oil boilers*

- The high impacts on water and abiotic resources are mainly due to the use of reservoir hydro electricity and the metal-based materials (Figure 5).

Acknowledgement

The work was carried out in the framework of GEothermie 2020 program, a collaboration between Services industriels de Genève (SIG) and the State of Geneva. The authors gratefully acknowledge SIG for their support.

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A stochastic method for spatial Multi-Criteria Decision Analysis: Application to Deep Geothermal Energy in Switzerland

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Introduction

The aim of this study is to develop a Multi-Criteria Decision Analysis (MCDA) Tool for Deep Geothermal Energy (DGE) systems in Switzerland. In particular, the tool aims to help decision makers to identify the most sustainable area for DGE plants using spatial MCDA, which combines Geographical Information Systems (GIS) capabilities with MCDA frameworks. The proposed approach uses a stochastic approach to combine spatial information from both explicit data (e.g., heat flow) and calculated ones (e.g., risk indicators, environmental impact indicators, etc.). For each indicator, marginal distributions for uncertain model inputs are generated based on specific *a priori* defined plant characteristics (e.g., capacities, number of drilled wells over lifetime). The marginal distributions are then used as input to the model to assess the sustainability of DGE in different areas of the Molasse basin, Rhine Graben, and Jura mountains regions.

Method

The spatial MCDA (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, a set of hypothetical power plants based on SCCER-SoE Phase 1 activities are considered (Table 1).

Table 1: Selected key physical parameters of DGE plant capacity cases considered in this study

Model Assumption	Unit	Doublet Plant			Triplet Plant		
		Poor	Base	Good	Poor	Base	Good
Net Plant Capacity	MWe	1.19	1.47	3.34	2.31	2.81	5.27
Life Time	years	20	20	20	20	20	20
Number of Wells	integer	2	2	2	3	3	3
Well Depth	km	5	5	5	5	5	5
Well Life Time	year	20	20	20	20	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]
	Proximity to Major Cities	Distance [km]

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 (ΔT) in the area of interest, since ΔT 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 and the Proximity to Major Cities (> 100000 inhabitants) indicators are considered in this study as a proxy of social acceptance, meaning that high risk(scale 3)/short distance are 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.

Marginal distributions for uncertain model in each area have been generated by fitting the indicator values estimated for each hypothetical plant. In general, uniform distributions fitted best each indicator in Table 2, except for the Proximity to Major Cities (lognormal distribution) and Natural Seismic Risk, where no variation among plants is considered, i.e. no marginal distribution has been further considered.

The generated marginal distributions have been used as input for the Stochastic Multi-criteria Acceptability Analysis (SMAA-TRI) [3] applied 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 (if considered) of the indicators and according to the cutting level (λ), which gives a measure on how demanding the decision maker is (i.e., lower λ implies that a better class is easier to be reached). In this study, λ and the marginal distribution of each indicator are arbitrarily distributed parameters analyzed using 10000 Monte Carlo simulations.

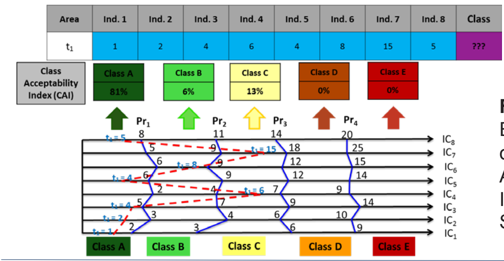

Figure 1: Evaluation steps of the Class Acceptability Index (CAI) in SMAA-TRI

Results

In this study, no stakeholder elicitation has been performed to assess weighting profiles, instead two approaches have been applied and compared:

- Missing information, where the indicator weights are sampled 10000 times using a Monte Carlo approach
- 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 based on sampling are presented in Figure 2. It clearly shows that DGE in Switzerland is considered from medium to highly sustainable, with the most sustainable areas being in North-East Switzerland.

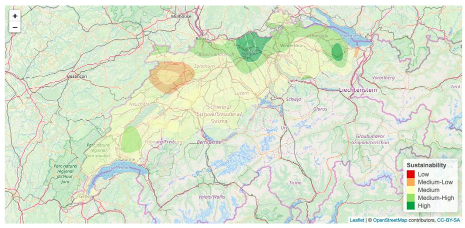

Figure 2: Sustainability map for DGE in Switzerland

Conclusions

- The application of a spatial MCDA based on a stochastic method with GIS capabilities, demonstrates its suitability as decision-making tool for deep geothermal energy in Switzerland.
- Results from the missing information profile, and the profiles representing equal weighting and focusing on environment are quite similar. Generally, areas in NE Switzerland perform best.
- Results focusing on the economic dimension strongly differ, with the Western part of Switzerland achieving Low and Medium-Low sustainability.
- When focusing on social indicators, results for most areas fall into the Medium-High and High sustainability categories.

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Energy system pathways with low environmental impacts and costs

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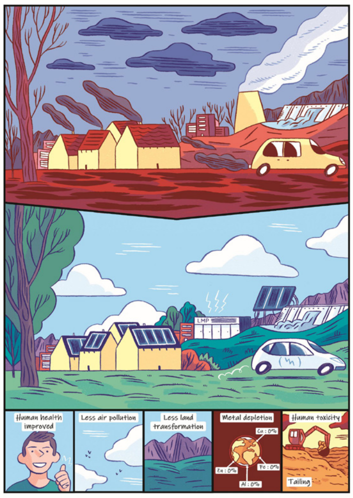
Introduction

Energy systems cause substantial environmental impacts, spanning climate change, air pollution, resource depletion and ecosystem degradations.



Energy system models (ESM) that guide energy policies by generating future energy pathways, at the national and regional level, offer limited insights into such environmental issues.

Solution: environmental indicators based on the life cycle assessment (LCA) methodology are integrated into an (ESM).

Methods

Swiss TIMES energy model is used to represent the Swiss energy system: electricity, heat, and transport.

19 environmental categories are assessed: IPCC Global Warming Potential (GWP 100) and the ReCiPe method.

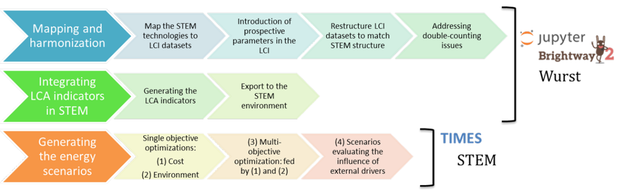


Fig. 1 integration LCA indicators into STEM and generating the energy scenarios, tools used per stage.

Energy pathways are generated for Switzerland up to the year 2050, resulting from the single- and multi-objective optimization of cost and environmental impacts.

Table 1 List of scenarios presented in the study, full name, primary objective, secondary objective(s), abbreviation, type and family

Energy scenario name	Primary objective	Secondary objective(s)	Abbreviation	Type	Family + (Background LCI databases)
Cost-optimized climate scenario	Cost	-	Clim, cost opt.	Single-objective optimization	Least-cost scenarios (BAU)
Cost-optimized Business as usual scenario	Cost	-	BAU, cost opt.	Single-objective optimization	Least-cost scenarios (BAU)
Least climate change scenario	Climate change	-	CC opt.	Single-objective optimization	Least-LCIA scores scenarios (BAU)
Least metal depletion scenario	Metal depletion	-	MDP opt.	Single-objective optimization	Least-LCIA scores scenarios (BAU)
Least human toxicity scenario	Human toxicity	-	HT opt.	Single-objective optimization	Least-LCIA scores scenarios (BAU)
Least climate change scenario, with σ % cost increase from optimal value	Climate change	Cost (relax. fac.: σ= 5%, 30 % and 50%)	CC opt., + σ % least cost	Multi-objective optimization	Least-LCIA scores scenarios with constraints based on the single-objective optimal value (BAU)
Least metal depletion scenario, with σ % cost increase from optimal value	Metal depletion	Cost (relax. fac.: σ = 5%, 15% and 30 %)	MDP opt., + σ % least cost	Multi-objective optimization	Least-LCIA scores scenarios with constraints based on the single-objective optimal value (BAU)
Least human toxicity scenario, with σ % cost increase from optimal value	Human toxicity	Cost (relax. fac.: σ = 5% and 30 %)	HT opt., + σ % least cost	Multi-objective optimization	Least-LCIA scores scenarios with constraints based on the single-objective optimal value (BAU)
Least climate change scenario, with σ % cost increase and μ % increase of metal depletion level from optimal values	Climate change	Cost (relax. fac.: σ = 5% and 30 %), Metal depletion (relax. fac.: μ = 5% and 30%)	CC opt., + σ % least cost & + μ % least MDP	Multi-objective optimization	Least-LCIA scores scenarios with constraints based on the single-objective optimal value (BAU)
Cost-optimized climate scenario, without additional investments on energy storage	Cost	-	Clim, cost opt., no battery	Single-objective optimization	Scenarios evaluating the influence of external drivers (BAU)
Least climate change scenario, without DAC and CCS technologies	Climate change	-	CC opt., no DAC & CCS	Single-objective optimization	Scenarios evaluating the influence of external drivers (BAU)
Cost-optimized climate scenario, with climate background LCI database	Cost	-	Clim, cost opt., Cli.DB	Single-objective optimization	Scenarios evaluating the influence of external drivers (Climate)
Least climate change scenario, with climate background LCI database	Climate change	-	CC opt., Cli.DB	Single-objective optimization	Scenarios evaluating the influence of external drivers (Climate)
Cost-optimized climate scenario, with climate background LCI database and least climate change value	Cost	Climate change (relax. fac.: μ = 0%)	Clim, cost opt., Cli.DB and least CC value	Multi-objective optimization	Scenarios evaluating the influence of external drivers (Climate)

Results

It is possible to generate energy pathways with low life cycle greenhouse gas (GHG) emissions with moderate increase in the costs (e.g. CC opt, +5% least cost).

Fig. 2 Cumulative cost (x-axis) against cumulative LCIA scores in terms of climate change (y-axis), metal depletion (size of the bubbles), and human toxicity (color scale) for the different scenarios between the years 2010 and 2050. The cost shown as relative to the cost-optimized climate scenario ('Clim, cost opt.', red circle). The metal depletion shown as relative to the optimal value from least metal depletion scenario ('MDP opt').

Minimization of the life cycle impacts on climate change generates:

(i) Trade-offs, increasing the impacts of metal depletion (i.e. large bubble) and human toxicity (i.e. color scale toward yellow) caused by the upstream extraction and manufacturing stages.

(ii) Substantial environmental co-benefits with regards to air pollution, ozone depletion, acidification, and land transformation (not in Fig.2).

Ambitious reduction targets of direct GHG emissions of 95% for the year 2050 might still result in substantial climate change impacts if emissions embodied in the infrastructure and upstream supply chain are not mitigated jointly (see red circle in Fig.2 cost-optimized climate scenario, and Fig.3.a)

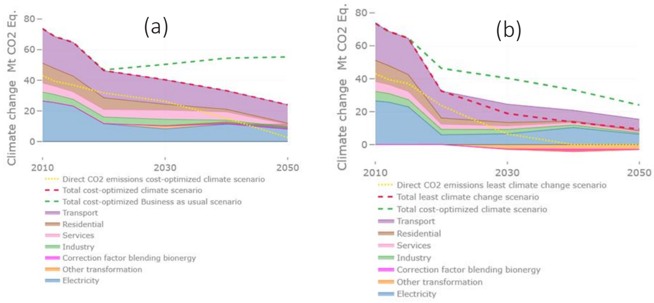


Fig. 3 Life cycle climate change impacts of the (a) cost-optimized climate scenario from 2010 to 2050, total, distribution per sector and comparison with the total impact of the cost-optimized business as usual scenario; (b) least climate change scenario from 2010 to 2050, total, distribution per sector and comparison with the total impact of the cost-optimized climate scenario.

Contributions

Multi-objective optimization allows to create pathways with minimized impacts at moderate cost.

The integration of the environmental impact minimization as an objective gives access to additional part of the solution space.

The environmental indicators consider the future evolution of the environmental performance of energy processes represented in the ESM, through prospective LCA including foreground and background LCI changes

This work is replicable to perform similar integration of LCA indicators either into other ESM or Integrated Assessment Models.

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Nonlinear Inverse Demand Curves in Electricity Market Modeling

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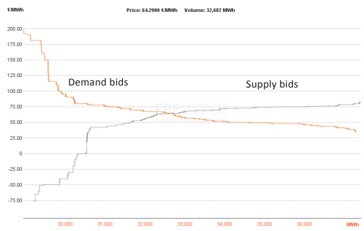
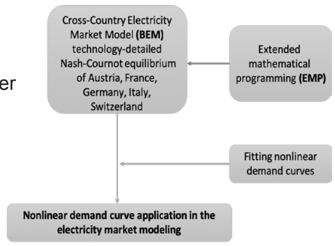
Motivations



- Provide a more accurate demand curve estimation which is close to real biding case
- Reduce the model Bias of Nash Cournot electricity market models with linear demand curves, which usually have higher prices and lower volumes than observed
- Give a proper estimation for the parameter in the conjectural variation mechanism in equilibrium models and improve the basic electricity market modeling for other scenarios

Numerical Implementation of Nonlinear Demand Curves

In order to implement nonlinear demand curves into electricity market modeling, a technology detailed model, the Cross-Border Electricity Market Model (BEM) and a new computational tool, EMP are combined.



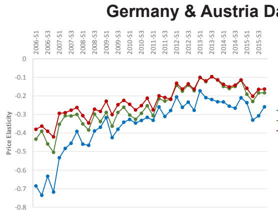
- BEM is an equilibrium model with market power where a Nash Cournot mechanism is implemented as well.
- EMP is a generalization framework that can derive optimality conditions automatically and allows multiple format models' reformulation, including MCP.

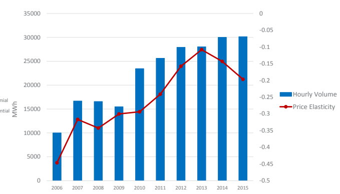
Results

Elasticity analysis of Germany and Austria day-ahead market:

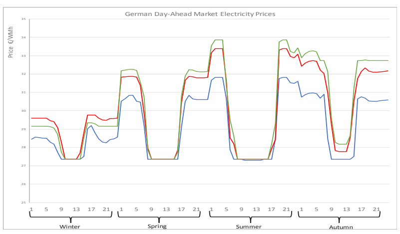
- Nonlinear curves give lower price elasticity estimation
- The absolute value of elasticity decreases over time:
- In 2010, the elasticity decreases due to renewable generation expansion
- After 2013, one of the reasons for the elasticity increase is the improved price forecast of players [preliminary]

Price Elasticity and Average Hourly Volume of Germany & Austria Day-ahead Market, 2006 - 2015



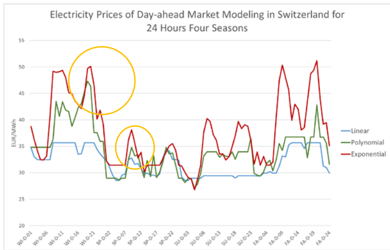


Impacts of the nonlinear inverse demand curves on electricity market modeling:
Using one representative nonlinear demand curve for 4 seasons × 24 day hours:



Results (cont.)

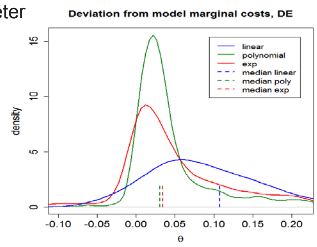
Using corresponding hourly fitted nonlinear demand curves for four seasons × 24 day hours:



Market prices with nonlinear demand curves are more volatile. In the low supply case prices with nonlinear demands are higher than in the high supply case, where prices between nonlinear and linear demand curves are close.

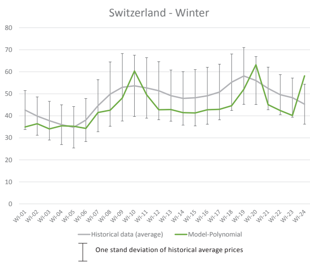
Improved conjectural variation parameter (θ) estimation:

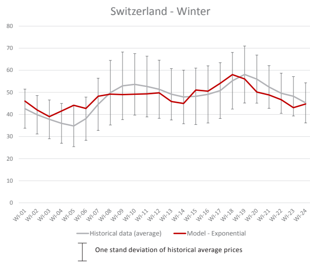
The Conjectural variation parameter is estimated to be lower by using nonlinear than by using linear demand curves.
Using the estimated θ, modeling results are close to the historical real market prices.



Conjectural Variation:

$$P(d) + d \cdot \theta \frac{\partial P(d)}{\partial d} - C = 0$$





Θ scaled by 60%

Conclusions

- Polynomial demand curves perform best in fitting the day-ahead electricity market data compared with linear and exponential ones.
- Nonlinear fitting inverse demand curves suggest lower elasticity estimations.
- Nonlinear inverse demand curves can be implemented to improve the electricity market modeling especially when market supply is low.
- Better explanation for large price deviations between market prices and marginal cost-based prices can be provided by models with nonlinear demand curves, even under the assumption of small market distortions.

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The potential & levelized cost of solar PV in Switzerland

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Introduction

- Update of levelized cost of electricity (LCOE) for solar PV in Switzerland with most recent data available
- Calculated:
  - Current & future LCOE
  - System size 6 -1000 kWp
  - Uncertainty ranges of LCOE
  - Sensitivity analysis for key parameters
- Associated for the first time the LCOEs for all the roofs in Switzerland with the potential of national annual generation

Methodology

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + D_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

LCOE Levelized Cost Of Electricity
I_t capital investment in the year t
M_t operations and maintenance cost in the year t
D_t decommissioning expenditures in year t
E_t annual electricity generation in year t (including degradation)
r discount or interest rate
n system lifetime

Related assumptions	Key source of reference
System investment cost	Solar offer check tool
Area, solar irradiance of roofs in Switzerland	Sonnendach
Annual O&M cost, Replacement cost	Toggweiler et al. 2018
System investment cost breakdown	Heiniger and Perret. 2017
General methodology, decommissioning cost	Bauer. et al. 2017

Results

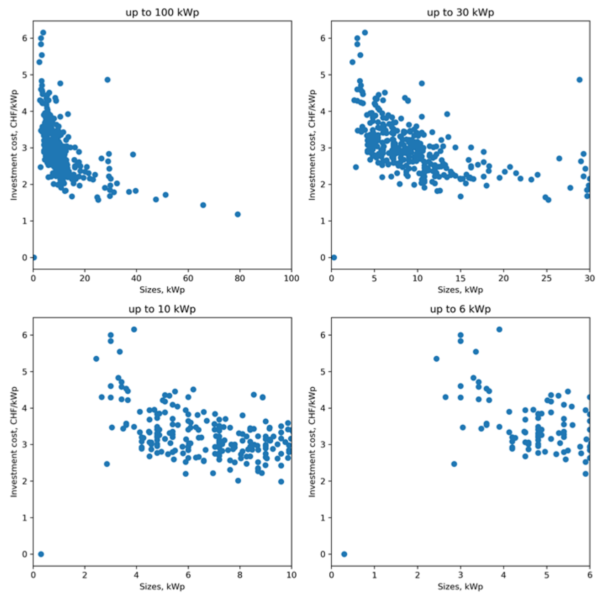

Figure 1: System investment costs of various system sizes in Switzerland, 2018; from top left to bottom right: size up to 100 kW_p, 30 kW_p, 10 kW_p and 6 kW_p.

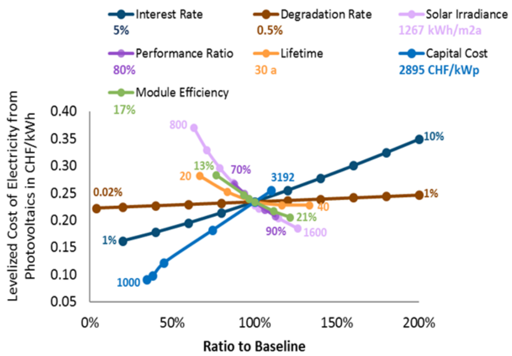

Figure 2: Sensitivity analysis for LCOE of a 10 kW_p system in 2018.

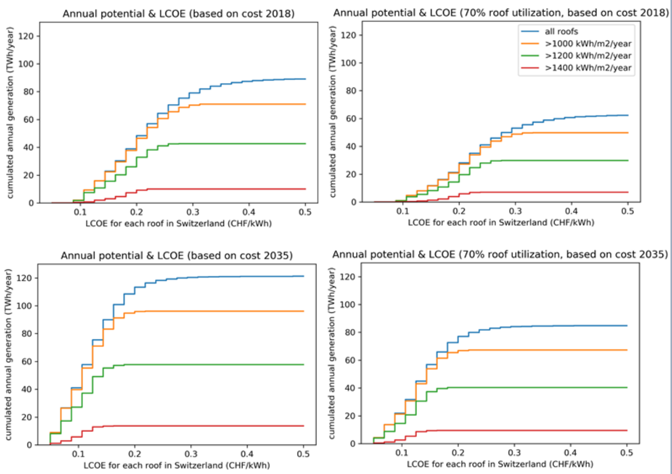

Figure 3: Annual electricity generation potential and LCOE for all roofs and solar irradiance of more than 1000, 1200 and 1400 kWh/m2/year, considering system investment cost in 2018 and 2035

Discussion & Conclusions

- Most of the installed PV systems in Switzerland are small-scale (less than 20 kW_p).
- LCOE is most sensitive to the solar irradiance, followed by system lifetime.
- The total generation potential in Switzerland is high (given the national annual consumption of 60 TWh of electricity), especially considering further cost reduction in the future.
- However, considering the actual utilization rate of roof and socially-acceptable LCOE will reduce the potential
- Future research should focus on investigating daily and seasonal generation pattern, local electricity tariff and consumption mix to better understand the possible potential

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