Task 4.2

Title

Global observatory of electricity resources

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Long term EU electricity supply scenarios: Impact of EU electricity policies on Switzerland

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The development of the Swiss electricity system will be highly influenced by technical, economic, and energy policy developments in the neighboring countries. To assess the impacts of key EU policies on the Swiss electricity system, the European Swiss TIMES Electricity Model (EUSTEM) developed at PSI is recalibrated to 2015 electricity data. Near-term EU energy polices are implemented along with new electricity storage options. *Preliminary* scenario analysis results show that gas power plants serves as transition technologies in the short-/mid-term. In our baseline, the committed EU polices for the electricity sector would reduce the sector's CO_2 emission in 2050 by 60% from 2010 level. To further decarbonize the electricity sector requires high share of renewable (>40% of the generation) and gas-based CCS technology. In order to integrate large shares of variable renewable energy production, 250-450 TWh of electricity would need to be shifted by storage systems in 2050. For the power sector alone, the marginal cost of CO_2 emissions reduction in 2050 varies between 300-445 CHF/t-CO_2 depending on the market conditions.

European Swiss TIMES model (EUSTEM)

The EUSTEM is a multi region, cost-optimization model of the EU electricity system. It has a long time horizon (2050+) and an hourly time resolution. The model covers 96% of EU-28 electricity supply (Fig. 1) with a detailed representation of the Swiss electricity system. The model is ***calibrated to 2015*** electricity statistics [1] and **technology characterisation** and **resource potentials** are updated. Now, new storage technologies and key **EU polices** are implemented. With the newly refined model, we conducted a scenario analysis of which we present ***preliminary results.***

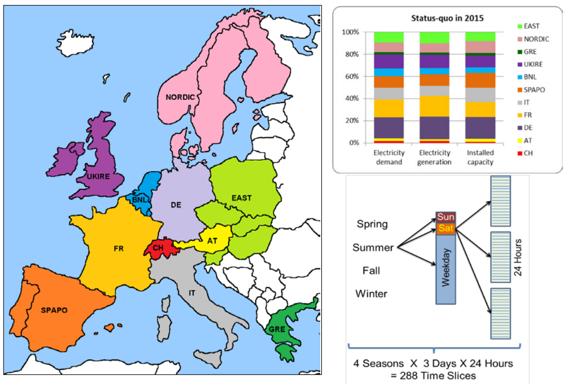

Fig 1. Regions in EUSTEM and intra-annual resolution

Electricity supply scenarios

Two core scenarios on future electricity supply, viz. *Base* and *Climate* scenarios.

- ***Base*** scenario: least cost electricity supply for the electricity demands from the EU reference scenario while fulfilling existing policy targets of EU member states, incl. nuclear phase-out, renewable targets and CO_2 emission, etc.
- ***Climate*** (*LC95*) scenario: reduction of the CO_2 emissions from the EU electricity sector by 95% until 2050 (from 2010 levels) without any national targets.

Variants*:* While curtailment of renewables is allowed in the core scenarios, we looked at a scenario without curtailment (*LC95_NoCurtail*). As a variant, self-sufficiency in electricity supply is considered in each region (*LC95_SS*).

Preliminary results in the *Base* scenario show a shift towards gas-based generation in the mid-term due to planned nuclear/coal phase-outs in some countries. In the long run, there is a growth in renewable based generation and coal based electricity with carbon capture and storage (CCS) which become cost-effective.

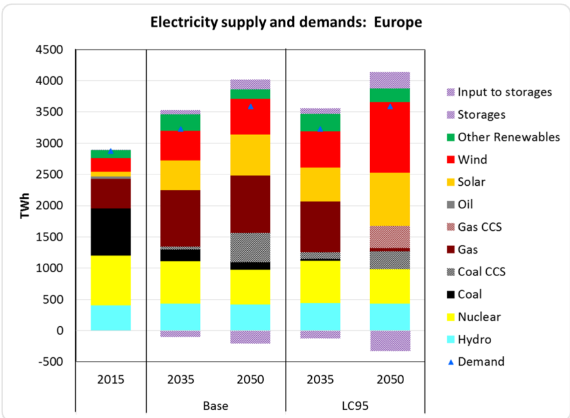

Fig 2. Electricity supply in the *Base* and *Climate* scenarios

In the *Base* scenario, EU electricity sector's CO_2 emissions reduce by 60% in 2050 relative to 2010 level. However, reducing the remaining CO_2 emission is challenging and incurs high cost. By 2050, over 700 GW of solar PV and 550 GW of wind turbines supply 40% of the electricity demand (Fig. 2) in the *LC95* scenario. This high share of RES requires large electricity storage (and curtailment) to cope with the diurnal and seasonal variabilities. At increasing climate change mitigation ambition, a shift from coal-CCS to gas-CCS can be observed to unlock further CO_2 emission reductions. This comes at high operational costs due to the increasing gas price. The marginal cost of CO_2 grows from 73 CHF/t CO_2 in 2030 to 300 CHF/t CO_2 in 2050. Additional renewables would need to be deployed together with additional storage capacity, in case CCS is excluded as an mitigation technology (*LC95_NoCCS* scenario in Fig. 3).

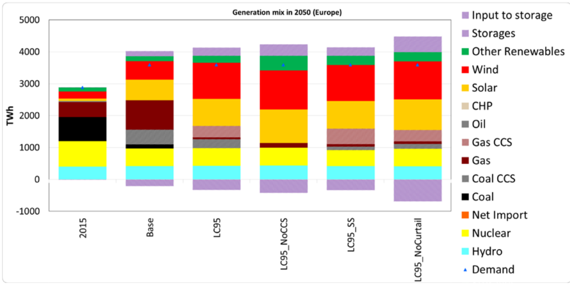

Fig 3: European electricity supply in 2050

The results indicate that some level of curtailment is cost-effective. In the non-curtailment scenario (*LC69_NoCurtail*), storage increases despite reduced investment in variable renewable technology.

If the regions would aim at maintaining autarky in their overall annual electricity supply while still using the flexibility from the EU network, the investments of renewable technologies are shifted to regions where their generation is less competitive compared to other regions while additional investments are needed for gas power plants and storages (Fig. 3).

Across the scenarios, the average cost of Swiss cross border electricity supply varies between 70 and 127 CHF/MWh in 2050 whereas the hourly spread of marginal cost is very significant (Fig. 4). When curtailment of solar PV and wind is restricted, the average cost in 2050 increase by about 11-20 CHF/MWh (from *LC95* levels). However, the hourly cost spread increases substantially with the occurrence of negative prices for few hours.

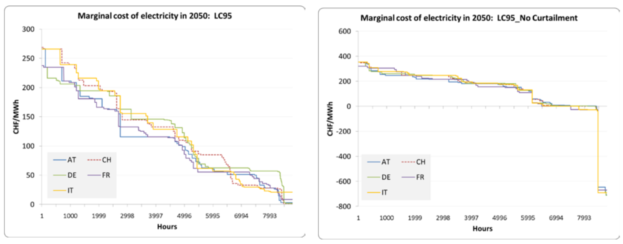

Fig 4: Cross border marginal cost of electricity in 2050 with and without curtailment

Summary

- Gas power plants serve as transition technologies in the short-/mid-term.
- The current EU polices and the least cost based electricity supply would reduce CO_2 emission of the power sector in 2050 by 60% (vs. 2010). To meet a 95% CO2 reduction target requires shares of intermittent renewable above 40% and large storage capacity with diurnal and seasonal storages.
- Depending on the market conditions, 125-355 GW of installed storage capacity store about 250-450 TWh electricity (or ~ 5-10% of the demands) in 2050.
- CCS-based technologies contribute cost-effectively to climate change mitigation.
- In the climate scenarios, marginal cost of CO_2 emissions reduction vary between 300-445 CHF/t-CO_2 in 2050 depending on the availaby of CCS, curtailment of production from renewable energy, and storage availability.

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Marginal electricity supply – a country-specific analysis on the global level

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Introduction

The long-term marginal electricity supply mixes of 40 countries were calculated and integrated into the consequential system model of version 3.4 of the ecoinvent Life Cycle Assessment (LCA) database.

In LCA, marginal electricity supply mixes are used to model the origin of the electricity consumed when one additional unit of a product is produced; this approach represents so-called "consequential LCA".

As such, the marginal mixes are composed only of electricity generation capacity able to react to a change in demand by a corresponding change in supply. In the case of long-term mixes, they reflect the accumulated effect of changes in demand for electricity on the installation and operation of new generation capacities.

In this study an overview of the methodology used to calculate the long term marginal mixes is provided. The influence of key parameters and methodological choices on the results is also evaluated.

Methods

The marginal electricity supply mixes were calculated using equation (1) from (Schmidt 2012; Muñoz et al. 2015):

$$Share_{i,TH} = 100 \cdot \frac{P_{i,TH} - P_{i,ref}}{\sum_i^n (P_{i,TH} - P_{i,ref})}$$

Where:
i: electricity-producing technology
TH: the year chosen as time horizon
ref: the year chosen as a reference for the time of the decision
P: the quantity of electricity generated at time "TH" or "Ref" by technology i
n: includes all unconstrained electricity producing technologies with a growing production at TH with respect to ref
Share i: the percentage that supplier i contributes to the marginal mix

The reference year is 2015 and time horizon is 2030. The formula is fed by data source from public projections from national and international authorities (e.g., European Commission, International Energy Agency, Swiss energy perspectives).

Results

In total, consistent electricity production scenarios were available for 40 countries. These were implemented, as displayed in Fig.1. The total electricity production originating from these countries accounts for 77% of the current global electricity generation.

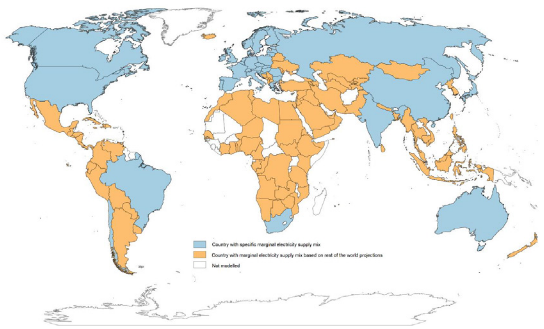

Fig. 1 Geographical coverage of the marginal electricity supply mixes in the consequential system model of ecoinvent v3.4, differentiated between countries where specific energy projections were used as a source of data and countries where rest of world shares were assumed.

The marginal electricity supply mixes are comprised, on global average, of 59% from renewable energy sources (RES), 27% from fossil-based sources and 14% from nuclear power.

Among the RES, onshore wind turbines dominate with an average share of 21% of the total mix and is followed by solar power with 17%.

In terms of fossil-based energy, natural gas combined cycle power plants are the largest marginal electricity source contributing 23%.

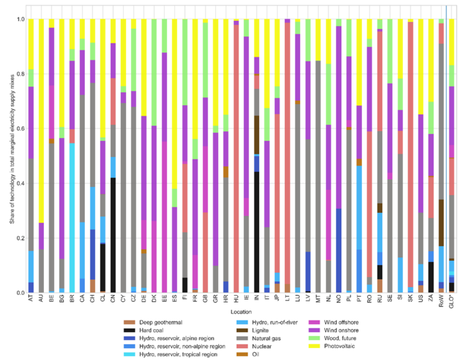

Fig. 2 Composition of marginal electricity supply mixes, as implemented in ecoinvent v3.4, consequential, at the low voltage level per country.

Impact assessment and local sensitivity analysis

Figure 3 shows the comparison of life-cycle emissions of CO_2 equivalents per kWh (CO_2-eq/kWh) between the mixes obtained in this study and other approaches to calculate the electricity mixes.

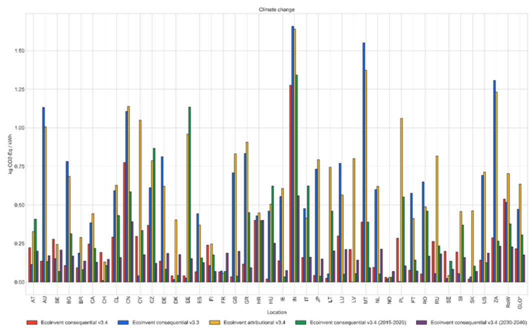

Fig. 3 Comparison of results for the climate change impact category (IPCC 2013, GWP 100a) of marginal electricity supply mixes in ecoinvent consequential v3.4, ecoinvent consequential v3.3, ecoinvent attributional v3.4 ("cut-off by classification"), ecoinvent consequential v3.4 (2015-2020) and ecoinvent consequential v3.4 (2030-2040).

The average life-cycle emission factor of the marginal mixes is 0.216 kg CO_2-eq/kWh and the median value amounts to 0.158 kg CO_2-eq/kWh. India has the highest emission factor with 1.275 kg CO_2-eq/kWh.

Conclusion

The marginal mixes integrated into the consequential system model of ecoinvent version 3.4 eliminate important limitations from the previous version of the database.

The use of energy scenarios allows for the accounting of the future evolution of the electricity system in line with the definition of electricity markets.

Reference
(1) Muñoz I, Schmidt J, De Saxcé M, et al (2015) Inventory of country specific electricity in LCA - consequential scenarios version3.0. Aalborg
(2) Schmidt JH (2012) Modelling of electricity in life cycle inventory and comparisons and recommended approach. In: SETAC Europe 18th LCA Case Study Symposium, 2012.

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Potentials, costs & environmental assessment of electricity generation technologies

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Background

This analysis represents an input to the next update of the Swiss Energy perspectives and serves as basis of the Energy Strategy 2050. Furthermore, it is part of the technology monitoring of SFOE. Consistent and up-to-date potentials and costs up to year 2050 are also important for the SCCER joint activity scenarios and modelling.

The work was commissioned by SFOE and supported by SCCER biosweet.

Scope

The following power generation technologies were evaluated:

Generation in Switzerland
- Hydropower
- Photovoltaics
- Wind turbines
- Electricity from biomass
- Deep geothermal power
- Fuel Cells
- Natural gas CC & CHP
- Nuclear

Electricity imports
- Offshore wind turbines
- Solar thermal power
- Wave and tidal power
- Coal

Potentials for electricity generation and supply

Exploitable electricity generation potentials were estimated until 2050: these potentials represent technical potentials reduced by environmental and economic constraints; social constraints are only partially taken into account.

Photovoltaic electricity generation represents the largest potentially far among the renewable energy carriers. Deep geothermal power generation is associated with the highest uncertainties due to lack of technology readiness.

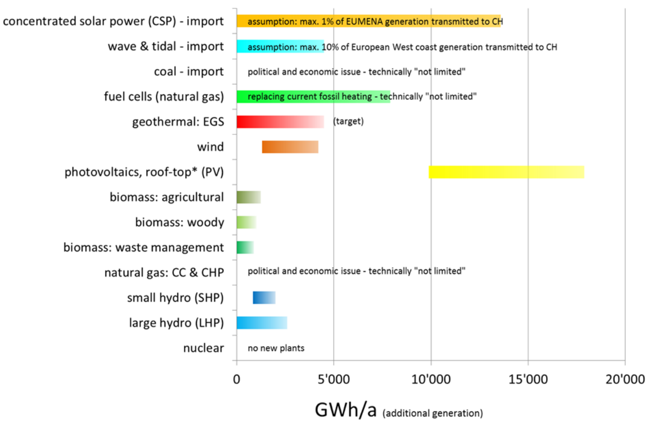

Figure 1: Estimated "exploitable potentials" for additional electricity generation (compared to 2015) with different fuels and technologies in Switzerland and for electricity imports from generation abroad, respectively, in 2050. NG: natural gas; CC: combined cycle; CHP: combined heat and power; LHP: large hydropower; SHP: small hydropower; CSP: concentrated solar power; PV: photovoltaics; EGS: enhanced geothermal systems; EUMENA: Europe, Middle East, North Africa; "coal" includes hard coal and lignite. * PV potential does not include generation by modules installed on building facades – the sustainable potential of such facade PV installations is in the range of 3-5.6 TWh/a.

Electricity generation costs

Levelised costs of electricity (LCOE) were estimated up to year 2050, taking into account expected developments of technology-specific investment, O&M and fuel costs. Compared to current generation costs, most substantial reductions can be expected for photovoltaics.

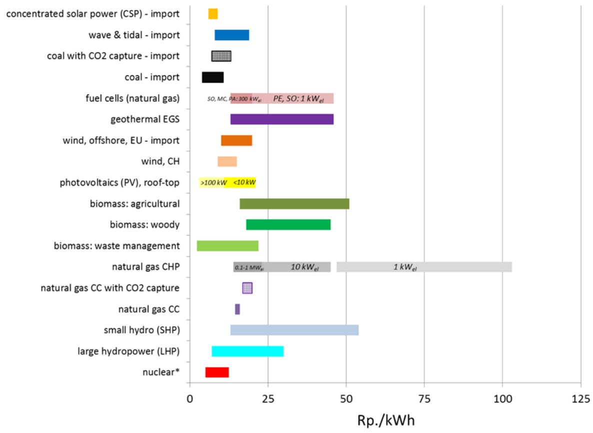

Figure 2: Costs of electricity generation (LCOE) with different technologies and fuels in year 2050.

Impact on climate change

Life-cycle greenhouse gas emissions were quantified, representing impacts on climate change. Life-cycle emissions include emissions due to construction, operation and end-of-life of power plants as well as fuel and material supply chains.

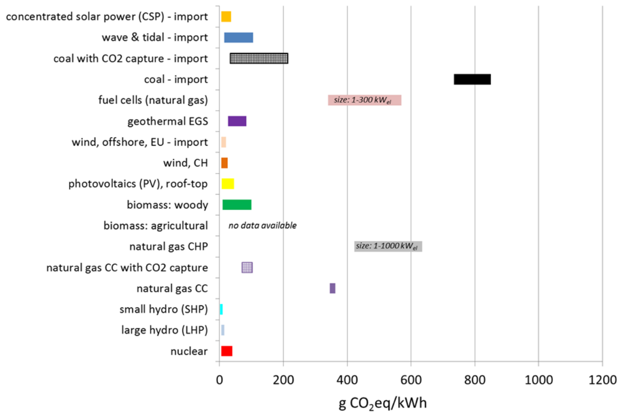

Figure 3: Life cycle GHG emissions of electricity generation technologies in year 2050.

Current limitations and further work

- Swiss-specific cost-potential curves – important for renewables – are currently not available and need to be established.
- Systemic issues such as short- and long-term electricity storage and the interconnection of the Swiss electricity market with the European electricity grid need to be investigated.
- External costs of power generation – important factor for technology assessment – should be quantified.

The final project report is available online: https://www.psi.ch/ta/PublicationTab/Final-Report-BFE-Project.pdf

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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 (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 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 (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 are arbitrarily distributed parameters analyzed using 10000 Monte Carlo simulations.

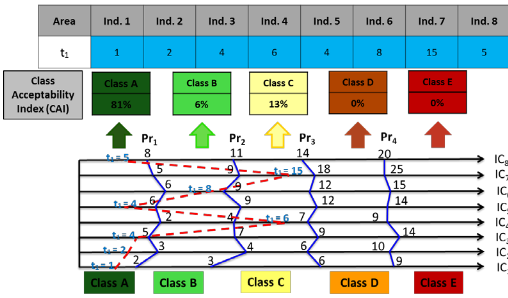

Figure 1: Evaluation steps of the Class Acceptability Index (CAI) in SMAA-TRI

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.

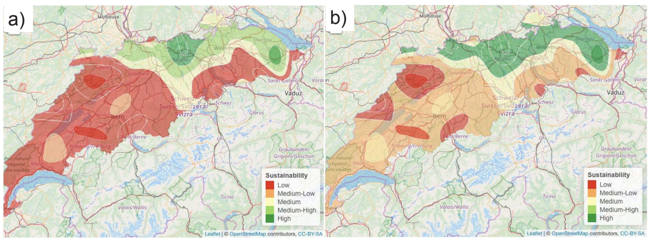

Figure 2: Environment-focused profile. a) Doublet Plant. b) Triplet Plant.

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

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Spatial hot spots and cold spots of new renewable electricity projects that received federal feed-in tariff in Switzerland

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Introduction

Spatially-resolved energy models with detailed renewable energy representation are widespread tools for informing renewable energy expansion, infrastructure planning and policy design [1]. A significant amount of evidence has shown that such models have represented the actual deployment of renewable energy very poorly [2]. An often-voiced argument is that existing models may not capture the real-world drivers and constraints of renewable energy diffusion comprehensively enough. In order to inform such models, we investigate the real-world spatial diffusion patterns of solar PV, small hydropower, biomass, and wind power projects in 2'222 Swiss municipalities. Using a dataset of feed-in tariff recipients in 2016 [3], we analyse to what extent the differences in renewable resource potential, electricity demand, environmental and socio-demographic characteristics determine the spatial heterogeneity in the deployment of new renewable electricity projects.

Methods

Two methods [4] are applied for investigating the spatial diffusion of renewable electricity projects in Switzerland: spatial analysis of hot spots and cold spots [5] and step-wise regression. These methods are applied on a spatially-explicit dataset of 11'545 solar PV, 270 biomass, 27 wind, and 527 small hydropower projects, using the number of projects as the primary variable of interest. The number of projects was chosen as the primary variable because it is a proxy for general level of activity in each municipality in terms of renewable projects and it is independent from the annual variations in electricity generation, for instance, due to weather. The analysis, first of all, is applied for Switzerland as a whole and then regional differences for transferability of insights are investigated.

Results

Fig. 1 shows the identified hot spots and cold spots of all types of new renewable electricity projects (Solar PV, biomass, small hydro, wind) in Switzerland in 2016. Additional graphs per technology were analysed as well. The main findings are:

- Spatial clustering of high vs. low density of new renewable projects can be distinguished from other areas, which supports the findings in previous literature [6] about the regional spillover effects
- Swiss hot spots, i.e. spatial aggregation of municipalities with above-average number of renewable projects, can be observed in the cantons of Glarus, St. Gallen, Luzern, and parts of Bern and Zurich
- Swiss cold spots with spatial aggregation of municipalities with below-average number of projects are located in the cantons of Vaud, Fribourg, Jura, and parts of Ticino
- Solar PV and small hydropower projects are more densely clustered, while wind and biomass projects diffuse more randomly dispersed

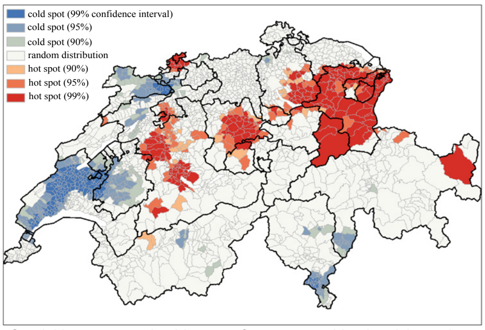

Fig. 1. Spatial hot spots and cold spots of new renewable electricity projects that received federal feed-in tariff in 2016

Table 1 summarizes additional findings:

- 359 Swiss municipalities (16% of all Swiss municipalities) fall in the category of hot spot and 478 municipalities (22%) are cold spots
- These 16% of municipalities that are hot spots include 35% of all new renewable electricity projects (4'380 projects) and cover 24% of electricity generation in 2016 in our dataset (455 GWh/year)
- 22% of municipalities that are cold spots include only 9% of all projects (1'145) and 8% of electricity generation (150 GWh/year)
- Hot spots generally have statistically significantly higher renewable electricity generation resource potential than cold spots
- Hot spots tend to be located in urbanized areas with high density of inhabitants, buildings and economic activity in the third sector
- Remote, rural and forested areas with a stronger forestry and agricultural activity tend to be cold spots
- Cold spots also have lower shares of conservative voters, higher shares of liberal voters and, interestingly, have supported stronger the Swiss Energy Strategy 2050
- The German-speaking region has the highest shares of hot spots (25%) while the French-speaking region has the highest share of cold spots (55%)

Table 1. Comparison of the municipal characteristics in the Swiss hot spots and cold spots of new renewable electricity projects and the other areas

Parameter	Units	Mean		
		Hot spots (99%, 95%, and 90% confidence)	Other municipalities	Cold spots (99%, 95%, and 90% confidence)
Overall characteristics				
Number of municipalities	municipalities	359	1385	478
Number of projects	projects	4'380	6'855	1'145
Number of projects per municipality	projects/municipality	12.2	4.9	2.4
Electricity generation in all renewable projects in 2016	GWh/year	455	1'262	150
Electricity demand and potential for renewable electricity generation				
Total electricity demand	GWh/(year·municipality)	50.6***	24.5	12.5*
Total renewable electricity potential	GWh/(year·municipality)	186***	151	95
Socio-demographic and other municipal characteristics				
Population	inhabitants	6920***	3639	1872**
Population density	inhabitants/km^2	603***	411	326*
German-speaking region	%	25	71	4
French-speaking region	%	1	44	55
Local economy				
Total number of employees	employees/municipality	4379*	2187	999
Share of employees in the first sector (raw material extraction)	%	12.8***	16.5	20.8***
Share of employees in the second sector (manufacturing)	%	27.3	26.4	24.5*
Share of employees in the third sector (services)	%	59.8**	56.7	54.1*
Political orientation and Energy Strategy 2050 vote				
Liberal left	%	22.4	22.5	27.4***
Liberal right	%	36.5	37.2	39.5**
Conservative	%	38.3	38.2	31.3***
Share of 'yes' vote for the Energy Strategy 2050	%	51.1	52.4	61.7***

Statistical significance for comparing hot spot and cold spots with the other municipalities: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Conclusions and discussion

- There is a substantial spatial heterogeneity across the Swiss regions and the types of renewable technologies, which originates to a large extent from the heterogeneity in renewable resource potential, especially for solar PV and small hydropower
- Densely populated and built-up areas with many available rooftops for solar PV or areas in the proximity of rivers for small hydropower plants are also the areas, where such projects primarily emerge
- Biomass power projects do not depend on biomass potential but rather on the presence of economic activity in the first sector
- The spatial diffusion of wind power in Switzerland is even less determined by the wind resource potential
- Some Swiss regions are still faster in deploying renewable projects with federal feed-in tariff than others, especially the German-speaking region. This finding is thus in line with previous literature [4] on regional spillover effects

References
[1] M. Welsch, et. al. Supporting security and adequacy in future energy systems: The need to enhance long-term energy system models to better treat issues related to variability, International Journal of Energy Research 39(3) (2015) 377-396.
[2] A.Q. Gilbert, et. al. Looking the wrong way: Bias, renewable electricity, and energy modelling in the United States, Energy 94 (2016) 533-541.
[3] Bundesamt für Energie, Liste aller KEV-Bezüger im Jahr 2016, 2017. http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=de&name=de_620208649.xlsx&endung=Liste%20aller%20KEV-Bez%FCger%20im%20Jahr%202016". (Accessed 15.05.2017)
[4] C. Thormeyer, et. al. Spatial dimension of renewable energy diffusion: empirical evidence on solar PV, biomass, wind, and small hydropower in Switzerland, Renewable Energy (under review).
[5] ArcMap, Hot Spot Analysis (Getis-Ord Gi*), 2018. http://desktop.arcgis.com/en/arcmap/latest/tools/spatial-statistics-toolbox/hot-spot-analysis.htm. (Accessed 25.05.2018).
[6] G.J. Allan, et.al. Green in the heart or greens in the wallet? The spatial uptake of small-scale renewable technologies, Energy Policy 102 (2017).

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