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Country-wide PV hosting capacity and energy storage requirements for distribution networks in Switzerland

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JASM final event

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Research questions

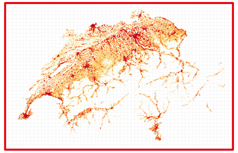
- Determine a country-wide model of the power distribution grid from proxy data.

- Compute the country-wide PV hosting capacity associated to the operational constraints of the determined power distribution grid models.

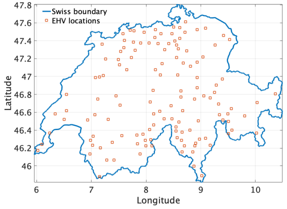
- Determine the cost-optimal size and sites of energy storage systems in the power distribution grid for different level of PV capacity.

Country-wide power distribution grid network models

Heat demand map (map.geo.admin.ch) → Scaling

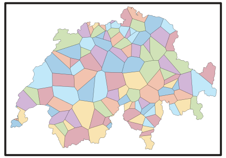


Country geographical boundaries



Extra high Voltage (EHV) (> 125 kV) substations locations (ENTSOE)

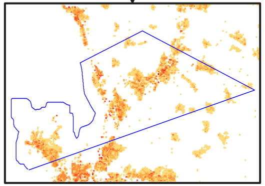
Voronoi partition (an electrical demand in certain area is served by the closest substation)

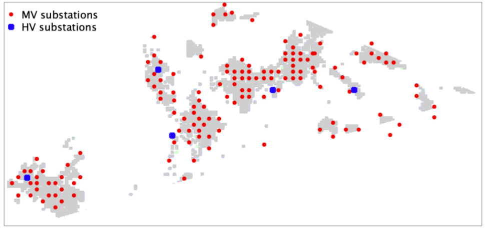


Electriciy demand map

Intersect

“EHV areas” Geographical region served by a EHV substation



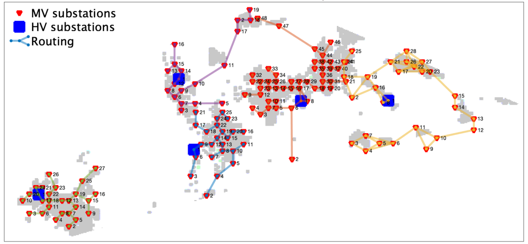


aggregate the demand till it reaches a threshold to place a substation.

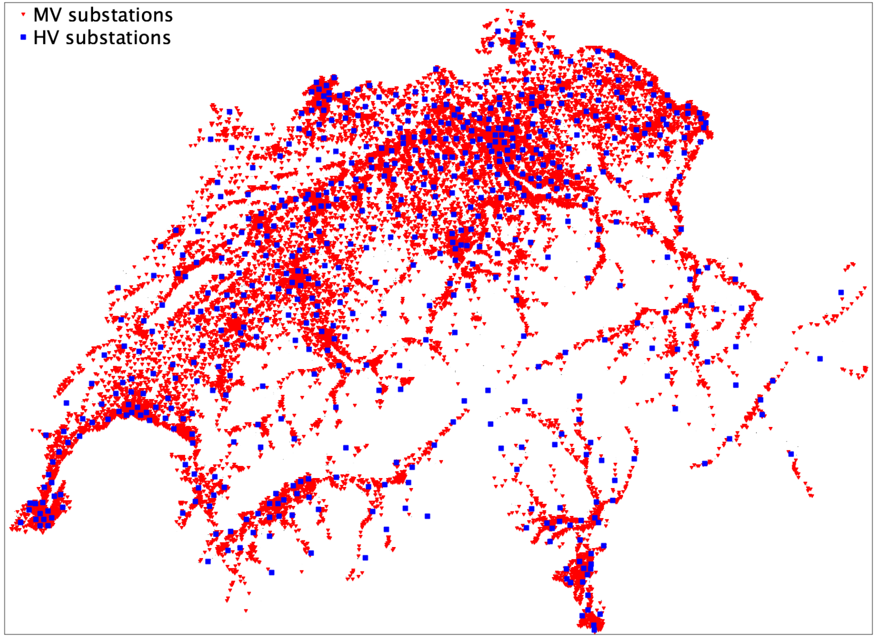
High Voltage (50 - 125 kV) and Medium Voltage (< 50 kV) nodes locations

Standard lines and transformers data from CIGRE

Routing algorithm MV networks



HV and MV locations for the whole Switzerland



Estimated locations of HV and MV substations

Statistics on HV and MV substations

Type	Number	Mean Demand	Max Demand
HV substations	776	10.9 MW	24.7 MW
MV substations	17,844	0.41 MW	0.97 MW

Number of identified grid components

Equipment	Number of elements
HV-MV transformers	776
MV-LV transformers	17'844 x 2 (for redundancy)
MV cables and overhead lines	1342.2 km

Data on estimated networks and their characteristics is available on https://github.com/DESL-EPFL/Estimated-Medium-Voltage-Distribution-Network-Models-for-Switzerland/

Full article on applied energy:

Gupta, Rahul, Fabrizio Sossan, and Mario Paolone. "Countrywide PV hosting capacity and energy storage requirements for distribution networks: the case of Switzerland." *Applied Energy* 281: 116010.

PV hosting capacity

- Formulate an optimal power flow (tractable and linear) to maximize the installed capacity of PV generation subject to grid constraints:

$$\underset{\{P_n^{\mathrm{pv}} \in \mathbf{R}^+, n \in \mathcal{N}\}}{\text{maximize}} \left\{ \sum_{n \in \mathcal{N}} \gamma_n P_n^{\mathrm{pv}} \right\}$$

Capacity factor (yearly energy produced per nominal capacity)

$$\begin{aligned}
\mathbf{p}_t &= \mathbf{p}_t^{\mathrm{pv}} - \mathbf{p}_t^{\mathrm{load}} && t \in \mathcal{T} \\
\mathbf{q}_t &= \mathbf{p}_t^{\mathrm{pv}} - \mathbf{q}_t^{\mathrm{load}} && t \in \mathcal{T} \\
\underline{\mathbf{v}} &\leq v(\mathbf{p}_t, \mathbf{q}_t, \mathbf{v}_0) \leq \overline{\mathbf{v}} && t \in \mathcal{T} \\
\mathbf{0} &\leq c(\mathbf{p}_t, \mathbf{q}_t, \mathbf{i}_0) \leq \overline{\mathbf{i}} && t \in \mathcal{T}, \\
0 &\leq s(\mathbf{p}_t, \mathbf{q}_t, \tilde{s}_0) \leq \overline{S} && t \in \mathcal{T},
\end{aligned}$$

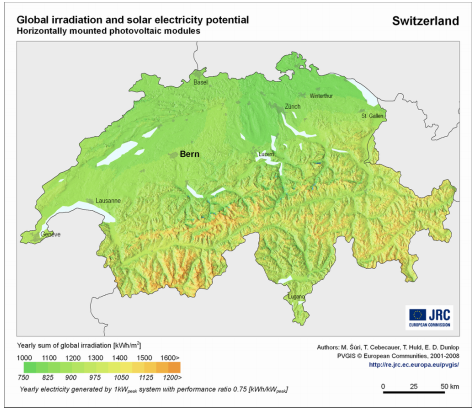
Grid constraints

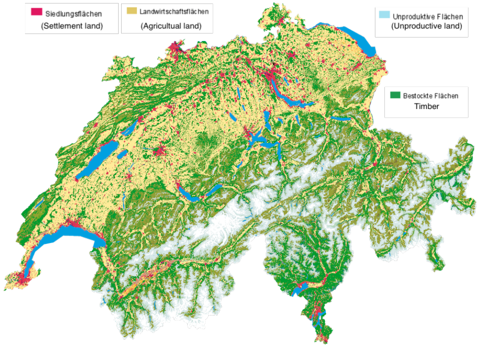
$$\begin{aligned}
p_{n,t}^{\mathrm{pv}} &= g(t, n, P_n^{\mathrm{pv}}) && t \in \mathcal{T}, n \in \mathcal{N} \\
P_n^{\mathrm{pv}} &\leq \overline{P_n^{\mathrm{pv}}} && n \in \mathcal{N}.
\end{aligned}$$

PV constraints

PV model (tilt/orientation)

Maximum PV using land-use constraint





Energy storage requirements

- Formulate an optimal power flow (tractable and linear) to minimize cost of installation subject to grid constraints and PV installation target:

Minimize costs

$$\underset{\mathcal{X}}{\text{minimize}} \left\{ \sum_{n \in \mathcal{N}} J\left(\overline{\gamma}/\gamma_n \cdot P_n^{\text{pv}}, P_n^{\text{bess}}, E_n^{\text{bess}}\right) \right\}$$

Grid constraints

$$\mathbf{p}_t = \mathbf{p}_t^{\text{pv}} - \mathbf{p}_t^{\text{load}} - \mathbf{p}_t^{\text{bess}} \qquad t \in \mathcal{T}$$

$$\mathbf{q}_t = \mathbf{p}_t^{\text{pv}} - \mathbf{q}_t^{\text{load}} - \mathbf{q}_t^{\text{bess}} \qquad t \in \mathcal{T}$$

$$\underline{\mathbf{v}} \leq v(\mathbf{p}_t, \mathbf{q}_t, \mathbf{v}_0) \leq \overline{\mathbf{v}} \qquad t \in \mathcal{T}$$

$$\mathbf{0} \leq c(\mathbf{p}_t, \mathbf{q}_t, \mathbf{i}_0) \leq \overline{\mathbf{i}} \qquad t \in \mathcal{T},$$

$$0 \leq s(\mathbf{p}_t, \mathbf{q}_t, \tilde{s}_0) \leq \overline{S} \qquad t \in \mathcal{T},$$

Battery constraints

$$\text{SOE}_{n,t} = \text{SOE}_{n,t-1} - p_{n,t}^{\text{bess}} \Delta t \qquad t \in \mathcal{T}, n \in \mathcal{N}$$

$$0 \leq (p_{n,t}^{\text{bess}})^2 + (q_{n,t}^{\text{bess}})^2 \leq (P_n^{\text{bess}})^2 \qquad t \in \mathcal{T}, n \in \mathcal{N}$$

$$aE_n^{\text{bess}} \leq \text{SOE}_{n,t} \leq (1-a)E_n^{\text{bess}} \qquad t \in \mathcal{T}, n \in \mathcal{N}$$

PV constraints

$$p_{n,t}^{\text{pv}} = g(t, n, P_n^{\text{pv}}) \qquad t \in \mathcal{T}, n \in \mathcal{N}$$

$$P_n^{\text{pv}} \leq \overline{P_n^{\text{pv}}} \qquad n \in \mathcal{N}.$$

$$\sum_{n \in \mathcal{N}} P_n^{\text{pv}} = P^{\star}.$$

→ Target PV installation

Energy storage requirements with PV installation

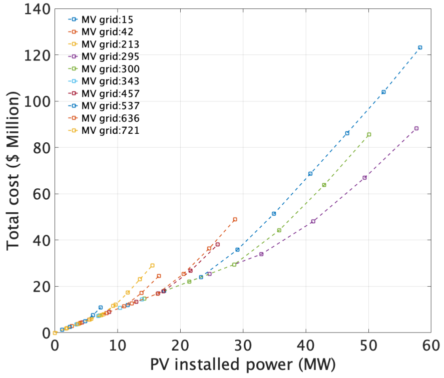
For each estimated MV network, we compute

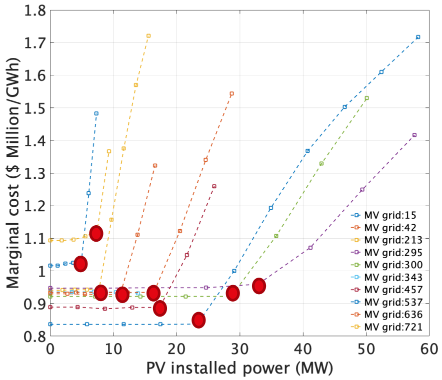
- PV hosting capacity,
- BESS size for PV increasing upto 300% of hosting capacity (or the land-use limit).
- We compute the total costs and marginal costs of installation for PV-BESS units.

$$\text{Marginal cost} = \sum_{n \in \mathcal{N}} \frac{J\left(\widehat{P}_n^{\text{pv}}, \widehat{P}_n^{\text{bess}}, \widehat{E}_n^{\text{bess}}\right)}{\widehat{P}_n^{\text{pv}} \cdot 365 \cdot 24 \cdot \gamma_n}$$

Costs of PV and BESSs

Component	Unit	Value
Turn-key PV system ($\mathcal{C}^{\text{PV}}$)	USD($)/kWp	1020
BESS converter rating ($\mathcal{C}^{\text{P}}$)	USD($)/kVA	200
BESS energy capacity ($\mathcal{C}^{\text{E}}$)	USD($)/kWh	300





- Cost sharply increase after PV hosting capacity due to BESS installation.
- Marginal costs differs for different network due to irradiance conditions.
- Is it more convenient to invest in BESSs to extend the hosting capacity of a grid with a large generation potential and installing here additional PV generation rather than in grids with lower generation potential to avoid installing BESS?

$$\underset{\{P_m^\star \in \mathbf{R}^+, m \in \mathcal{M}\}}{\text{minimize}} \left\{ \sum_{m \in \mathcal{M}} \mathcal{P}_m^{\text{pv}} f_m(\mathcal{P}_m^{\text{pv}}) \right\}$$

$$\underline{P}_m^\star \leq P_m^\star \leq \overline{P}_m^\star \qquad m \in \mathcal{M}$$

$$\sum_{m \in \mathcal{M}} P_m^\star = P^{\text{target}}.$$

Empirical marginal cost function

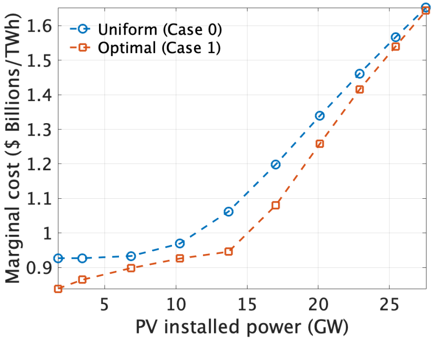
Target PV at the level of whole Switzerland

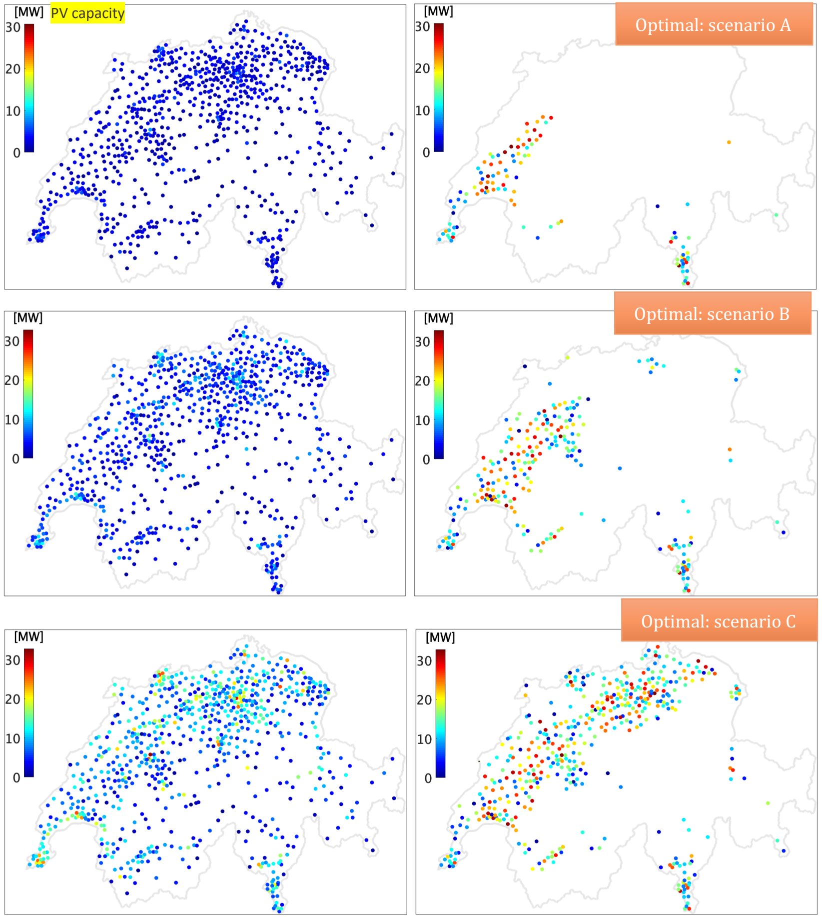
Optimal vs uniform installation of PV and storage

Uniform (case 0): PV installation in proportional to their maximum capacity due to land-use constraint.
Optimal (case 1): Minimizing the cost at the level of whole country (favoring lower marginal cost location).

Scenario	PV installed capacity (GWp)	PV production (TWh/y)		BESS Power (GW)		BESS Capacity (GWh)		Total cost Billions $	
		Case 0	Case 1	Case 0	Case 1	Case 0	Case 1	Case 0	Case 1
A	1.71	1.90	2.11	0.00	0.00	0.00	0.00	1.76	1.77
B	3.43	3.81	4.09	0.00	0.00	0.00	0.01	3.53	3.53
C	6.85	7.62	7.87	0.03	0.01	0.14	0.01	7.11	7.07
D	10.28	11.42	11.46	0.46	0.04	1.31	0.05	11.07	10.61
E	13.70	15.23	15.25	1.74	0.51	5.73	0.68	16.18	14.42
F	17.02	18.92	18.99	3.64	3.08	14.74	7.88	22.68	20.51
G	20.11	22.36	22.43	5.87	5.67	26.83	21.26	29.94	28.23
H	22.89	25.44	25.46	8.10	7.94	39.90	36.20	37.17	36.03
I	25.42	28.24	28.25	10.18	10.08	53.41	51.00	44.25	43.50
J	27.57	30.61	30.61	12.07	12.00	65.87	65.04	50.57	50.31

Scenarios corresponding to 5, 10, … , 100% of maximum PV by land-constraint





Summary

- We estimated likely distribution grids starting from publicly available georeferenced data.

- We then present a computationally tractable method based on a linearized OPF problem to compute the PV hosting capacity of distribution grids.

- We account for distributed potential of PV generation and land-use constraints, modelled with highly resolved PV capacity factors from PVGIS, which include shading from topographical features along the horizon.

- Finally we propose and solve a specific planning problem that determines a cost-efficient allocation of PV_BESS system across the whole country.

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Thank you

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Questions?

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