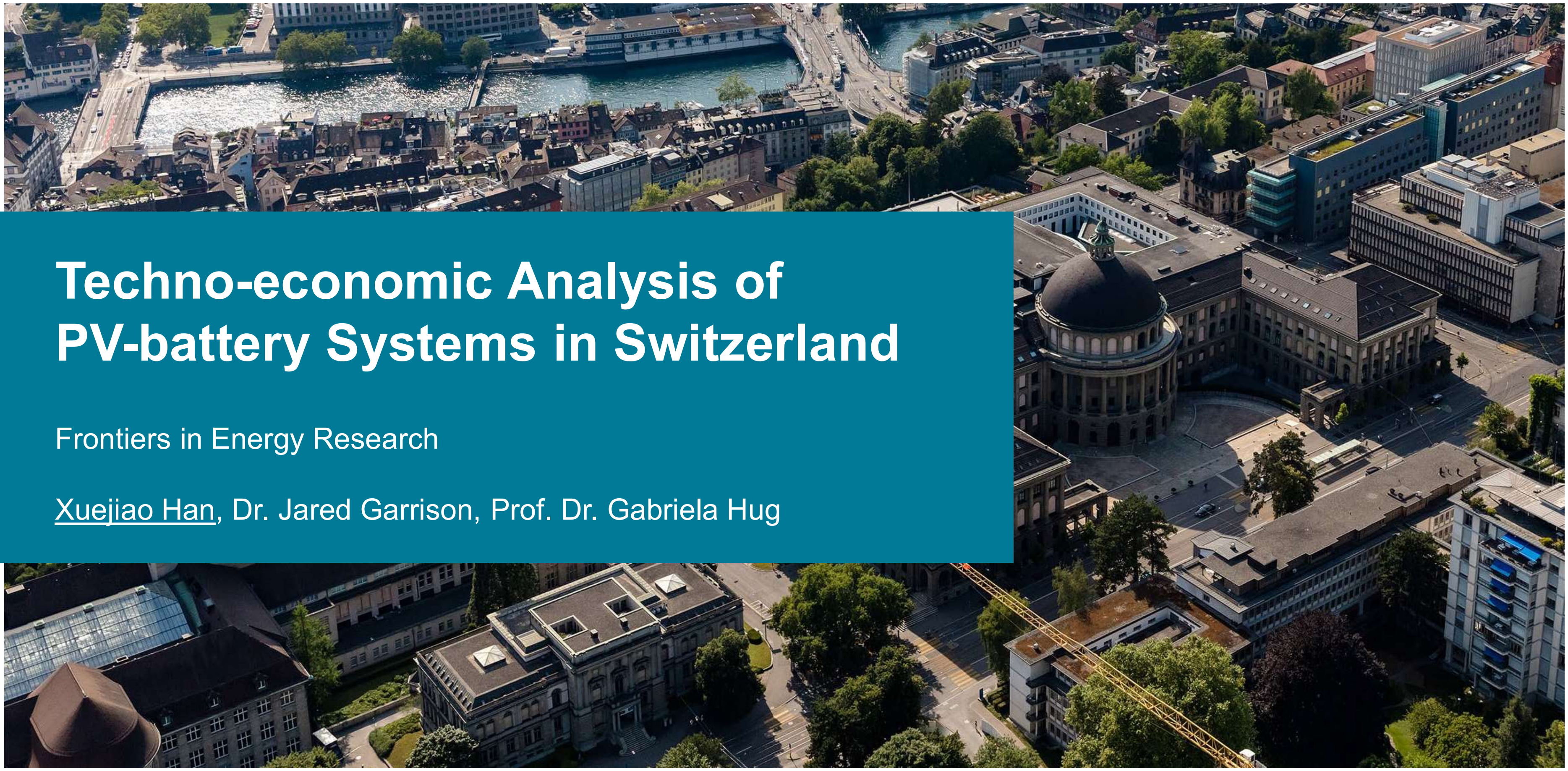
ETH zürich

Power Systems Laboratory



Techno-economic Analysis of PV-battery Systems in Switzerland

Frontiers in Energy Research

Xuejiao Han, Dr. Jared Garrison, Prof. Dr. Gabriela Hug

Outline

- Background and Motivation
- Problem Description
- Input Data and Setup
- Selected Results
  - Single Customer Group’s Level
  - Regional / Cantonal Level
  - National Level
- Conclusions
- Limitations and Future Work

Electricity Power Systems in Transition

Background & Motivation

Demand Response

Technology Improvement

Electric Vehicle

Energy Storage

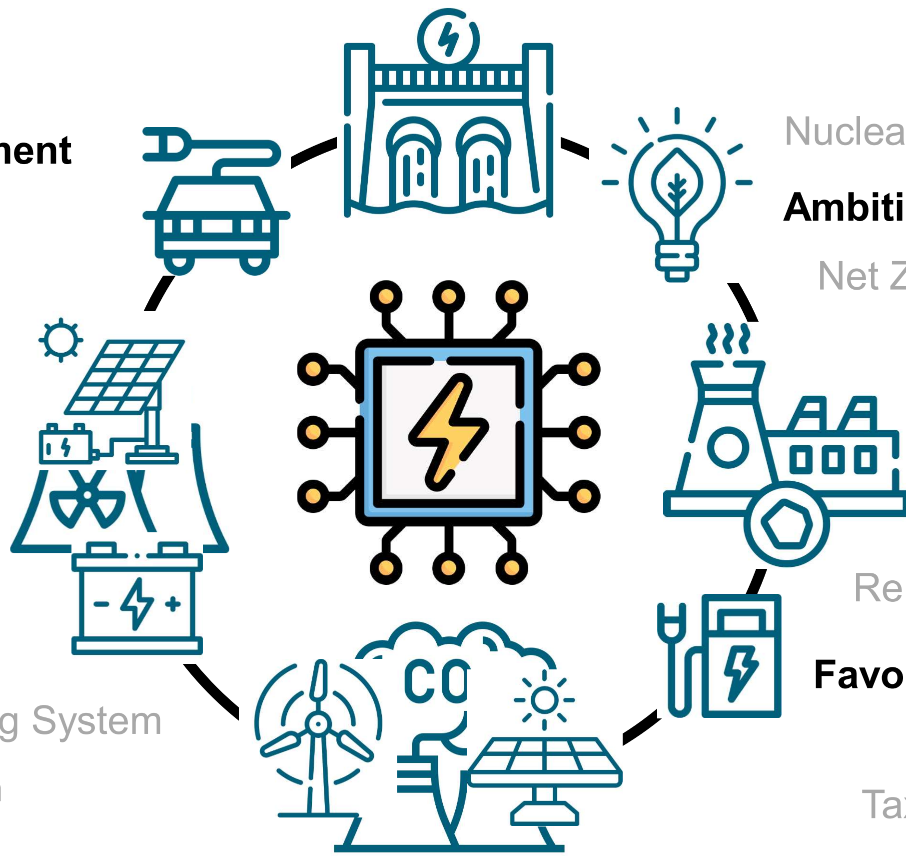
Cost Reduction

Solar Panel

Wind Power Plant

Transportation Heating System

Electrification



Renewable Target

Nuclear Phase-out Coal Phase-out

Ambitious Energy & Climate Targets

Net Zero Greenhouse Gas Emission

Digitalization

Feed-in Tariff

Renewable Subsidy

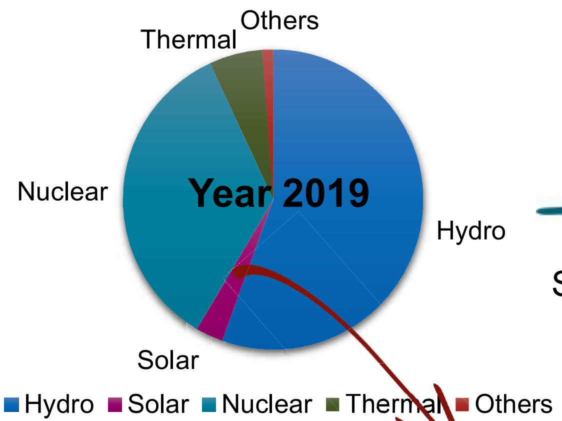
Favorable Government Policy

Injection Remuneration

Tax Credit

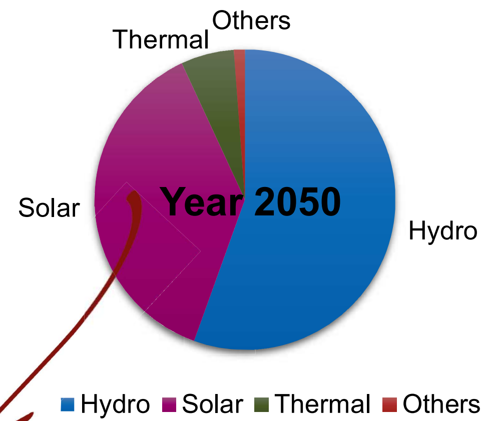
Status of PV and Battery in Switzerland

Significant amount of PV needs to be installed to meet policy targets



Source: BFE, Gesamtenergiestatistik 2019[5]

Energy Strategy 2050[1]
Nuclear Phase-out
Net Zero



Solar: high social acceptance
high deployment potential (67 TWh[2])

Cum. 2.5 GW[3] (2.1 TWh, 3.3% demand)
+ 327 MW/year[3]

+ 1.6 GW/year[4] → **Add 50 GW[4]**

Research Questions:

- How are the PVB system economics affected by customer group heterogeneity?
- What are the expected cumulative PVB system investments at regional and national levels over the coming years?
- How sensitive is the economic viability of the PVB system to uncertainties related to costs, load profiles, electricity prices, etc.?

Customer Group Heterogeneity

Customers clustered based on rooftop size, annual irradiation, electricity consumption and region

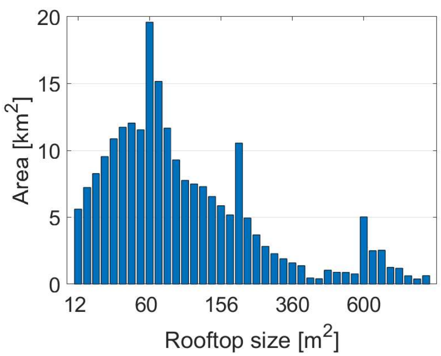
Sonnendach dataset[6], 630 km^2

Rooftop size > 10 m^2 & Irradiation > 1000 kWh/m^2

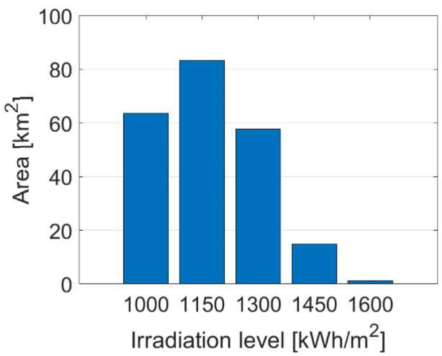
Rooftop availability, building types, warm water consumption

~4 million rooftop data entries, 224 km^2

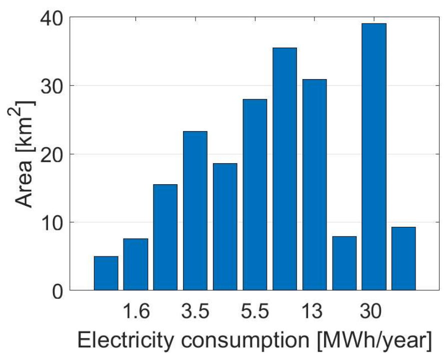
40 Rooftop size categories



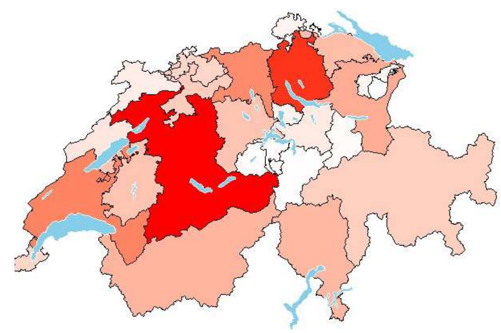
5 Irradiation levels



11 Consumption categories



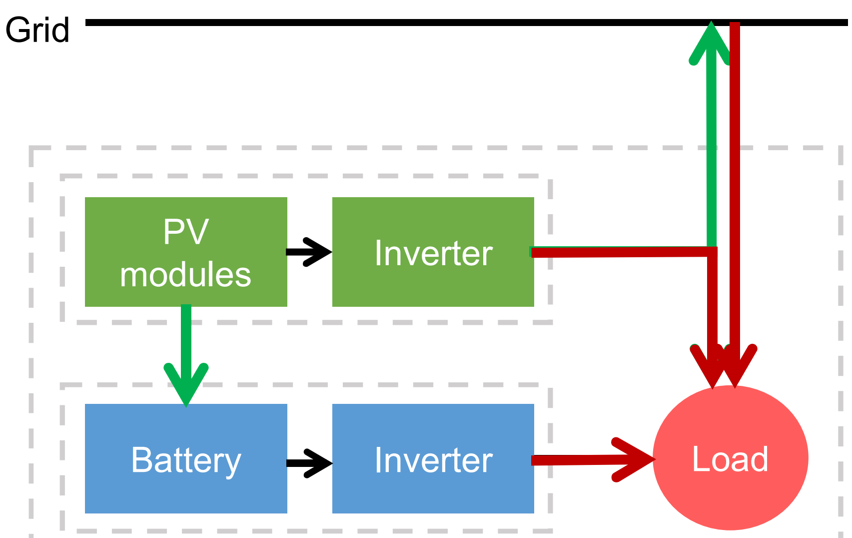
26 Regions



57’200 Customer groups

Economics of the PV-battery System Investment

Evaluate each customer group using the median values from within each group



To optimize:

- Investment decisions (PV, battery energy & power capacities)
- Operational decisions over all 8760 hours

Main constraints:

- PV investment capacity limited by rooftop size
- Power from the PV units could:
  1) charge the battery
  2) supply the demand
  3) be injected back to the grid
- Demand can be satisfied by:
  1) power from PV
  2) power from the battery
  3) power from the grid

Economics of the PV-battery System Investment

Evaluate each customer group using the median values from within each group

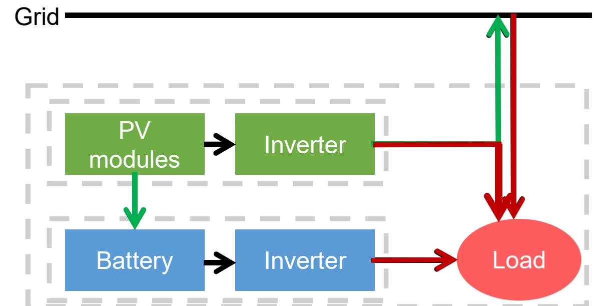
Objective:

$$\max \sum_{c\in C}\left[-C_c^{\text{inv,pv}} - C_c^{\text{inv,bat}} + \sum_{y=y_0}^{l^{\text{sys}}} \frac{R_{y,c}^{\text{in}} - C_{y,c}^{\text{out}}}{(1+wacc)^y} - \sum_{y=y_0}^{\lfloor (l^{\text{sys}}-1)/l^{\text{bat}} \rfloor} C_{y'=l^{\text{bat}}n'+1,c}^{\text{rpl,bat}} + R_c^{\text{res,bat}}\right]$$

Net inv. cost
- inv. subsidy
- tax rebate

Net cash flow

- bat reinv. cost + res. value



$$R_{y,c}^{\text{in}} = \sum_{t=1}^{T} \left(p_{t,c}^{\text{p2g}} p_{y,t,c}^{\text{inj}} + p_{t,c}^{\text{sc}} pr_{y,t,c}^{\text{retail}}\right)\left(1-\delta^{\text{deg}}\right)^{y-y_0}$$

inj. profit — SC saving — degradation

Cash inflows: Injection profit + Savings from self-consumption

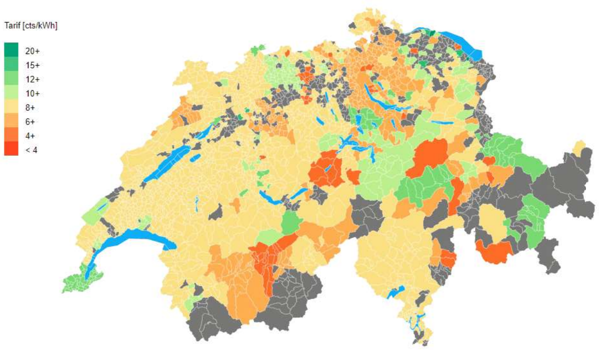
$$C_{y,c}^{\text{out}} = \sum_{t=1}^{T} \left(\sum_{p\in P} c_p^{\text{voc,pv}} gen_{t,p,c}^{\text{pv}} + c^{\text{voc,bat-e}} p_{t,c}^{\text{dis}}\right) + c^{\text{foc,bat-p}} cap_c^{\text{bat-p}}$$

var. op. cost — fix op. cost

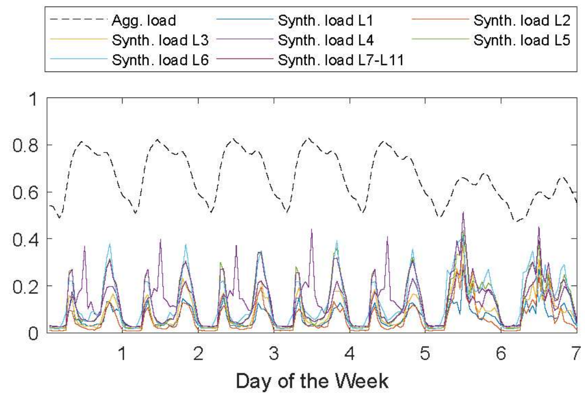
Cash outflows: Variable and fixed operating cost

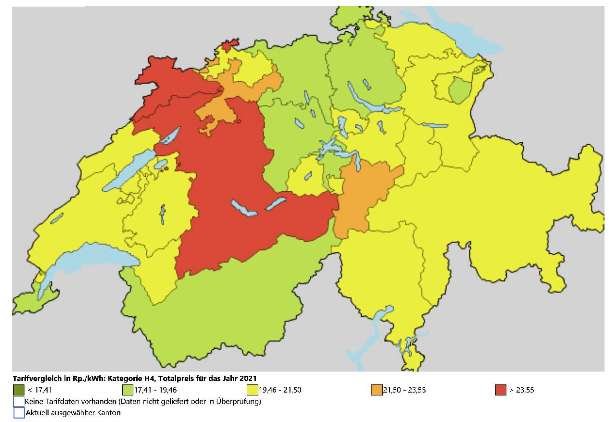
Input Data and Setup

Policy and regulation assumptions



Source: VESE





Source: Elcom

Support policy:

- Investment subsidy data from BFE, which is assumed to decrease by 20% from 2020 to 2030, then immediate phase-out
- DSO injection tariff (Vergütungstarif) based on data from VESE

Electricity load profile:

- Load profiles of consumption categories L1-L11 are generated using different load profiles produced by "LoadProfileGenerator"

Retail electricity tariff:

- Based on data of different consumption groups from ElCom (including grid charge and additional fees)

Baseline Results for an Example Customer Group

Optimal PV and battery investment sizes increase over time with PBP fluctuates in early years

Year	Investment size [kW or kWh]			PBP [Year]	SCR	SSR
	PV	BESS-e/BESS-p	C-rate			
2020	0.0	0.0	n/a	n/a	n/a	n/a
2025	2.0	3.0 / 0.6	0.20	13.5	74%	29%
2030	2.3	5.7 / 1.0	0.19	11.8	80%	36%
2035	2.7	7.2 / 1.4	0.20	13.0	80%	42%
2040	3.3	8.6 / 1.8	0.21	11.7	77%	48%
2045	6.0	10.0 / 2.3	0.23	11.4	56%	64%
2050	6.0	10.3 / 2.3	0.22	9.5	56%	65%

PBP: Payback period
SCR: Self-consumption rate
SSR: Self-sufficiency rate

Information of the example customer group:

- Electricity consumption: 5025 kWh/year
- Solar irradiation: 1212 kWh/m^2
- Rooftop size: 113 m^2 (i.e. 18.8 kWp PV)

- PV and battery sizes increase over time
  - decreasing cost
  - increasing retail electricity tariffs
- C-rate fairly consistent over the years
- Payback period (PBP) in general decreases except for 2030-2035
  - subsidy expiration by 2030
- Self-consumption rate (SCR) first increases and then decreases
  - early year investment driven by high SCR
  - future year investment driven by decreasing cost, profitable to install a PVB system that is larger than required for the consumers' demand.
- Self-sufficiency rate (SSR) increases over time

Baseline Results for Canton Zurich

Weighted-average (WAVG) results for 2200 customer groups in Zurich

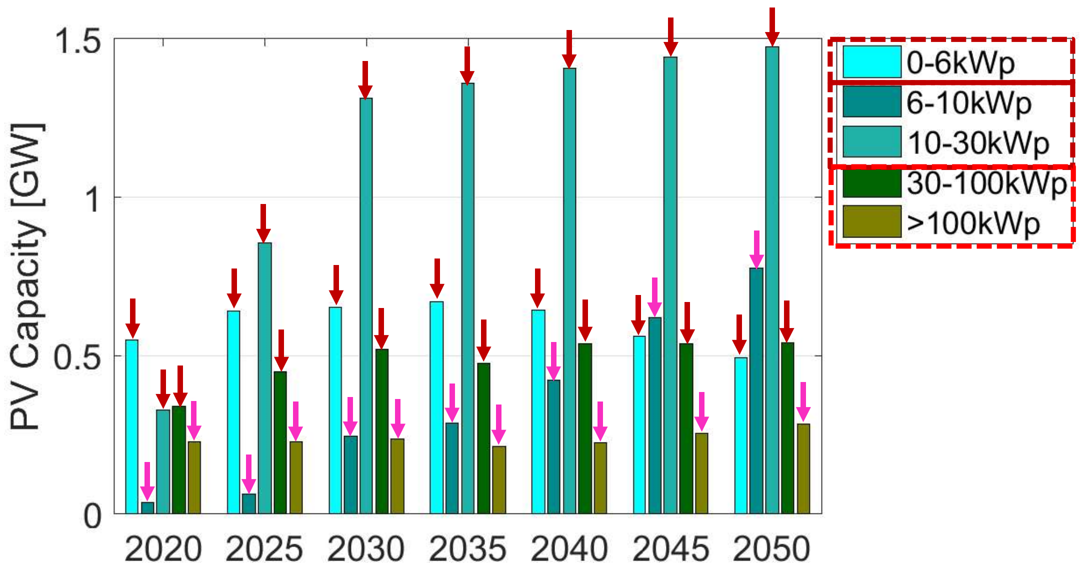
Year	WAVG investment size [kW or kWh] PV	BESS-e/BESS-p	C-rate	WAVG PBP [Year]
2020	4.5	1.1 / 0.3	0.25	11.5
2025	5.8	7.0 / 1.5	0.21	11.7
2030	7.6	14.0 / 2.8	0.20	11.0
2035	7.8	16.7 / 3.4	0.20	11.6
2040	8.3	18.1 / 3.7	0.20	10.2
2045	8.8	18.9 / 3.9	0.20	9.3
2050	9.2	19.8 / 4.0	0.20	8.3

WAVG: Weighted-average
PBP: Payback period

- Weighted-average size of PV and battery investments is increasing over time
- Weighted average PBP fluctuates between 2020 and 2035 and decreases afterwards
  - mixed impacts of subsidy, cost and tariffs
- Profitable to invest in PV and PV-battery for some customer groups already in 2020

Baseline Results for Example Canton Zurich

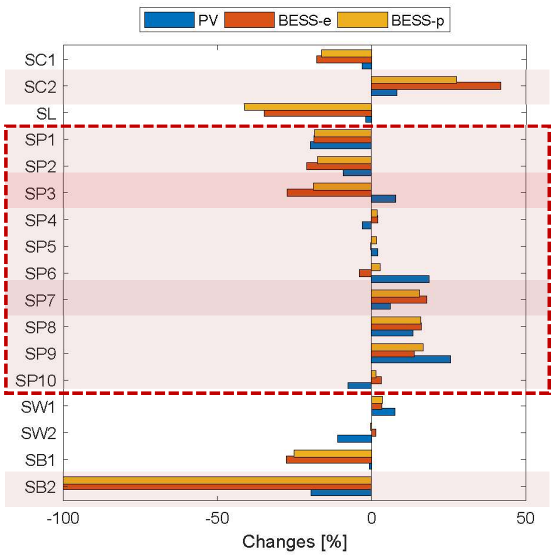
Results for 2200 customer groups in Zurich



- PV < 6 kW first increase then decrease
  - early year investments driven by high self-consumption rate (customers install PV that do not fully exploit the rooftop potential)
- PV 6-30 kW increase significantly over time
- PV > 30 kW increase over time except for 2030-2035
  - expiration of investment subsidy by 2030

Sensitivity Analysis Results for Example Canton Zurich

Results for 2200 customer groups in Zurich, year 2050

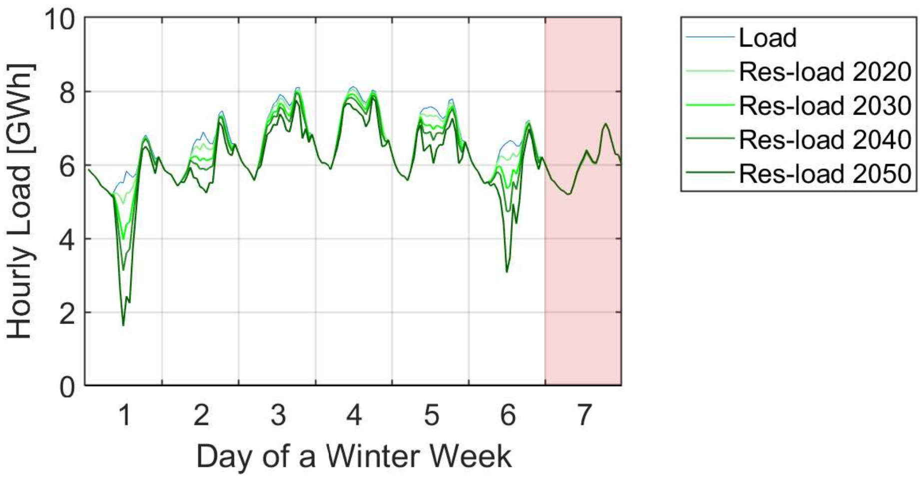


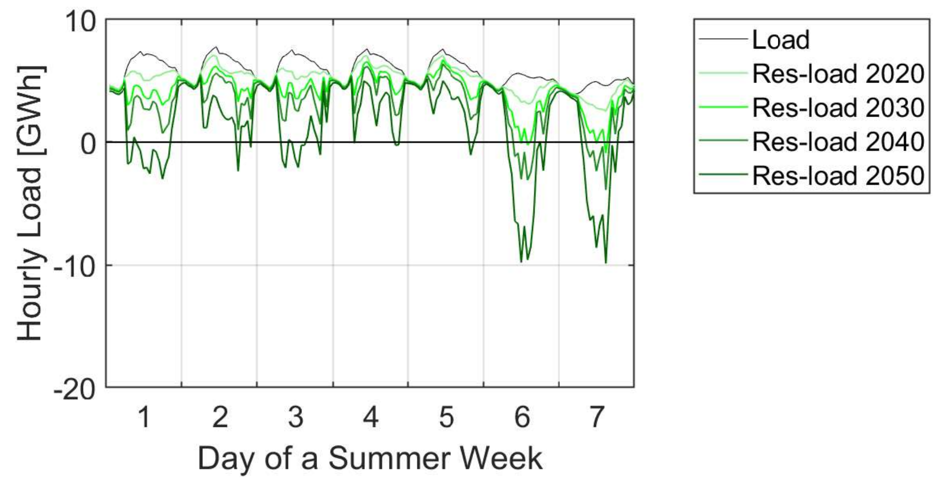
Scen.	Changed parameters	Remarks
SC1-2	PV and battery costs	A high cost (SC1) and a low cost scenario (SC2)
SL	Load profile	Individual load profiles replaced by the aggregate profile
SP1-9	Retail and wholesale el. price development	Access to wholesale market; injection tariff replaced by hourly wholesale price
SP10	Retail el. price development; injection tariff	No access to wholesale market; injection tariff is zero
SW1-2	WACC	A 2% WACC (SW1) and a 8% WACC scenario (SW2)
SB1-2	Battery price; battery investment	Battery price adjusted using Tesla price in Switzerland (SB1); battery forced not to be invested (SB2)

- Optimal PV investment capacity is highly sensitive to the electricity price developments (i.e., SP1-SP10)
  - lowest/highest price scenario (i.e., SP1/SP9) yields the lowest/highest level of PV integration
- Cumulative battery energy and power capacities vary significantly among scenarios
  - SC2: low cost yields highest level of battery integration
  - SB2: Swiss cost yields lowest level of battery integration
- Electricity price scenarios SP1-SP10
  - highest retail price increase of 2%/year and lowest wholesale price increase of -1%/year (i.e. SP7) → highest battery investment
  - lowest retail price increase of 0%/year and highest wholesale price increase of 3%/year (i.e. SP3) → lowest battery investment
  - smaller spread between wholesale and retail electricity prices decreases the profitability of battery investments

Dynamic Pattern of the Hourly Swiss Residual Load (10-year PBP)

The system's need for flexibility



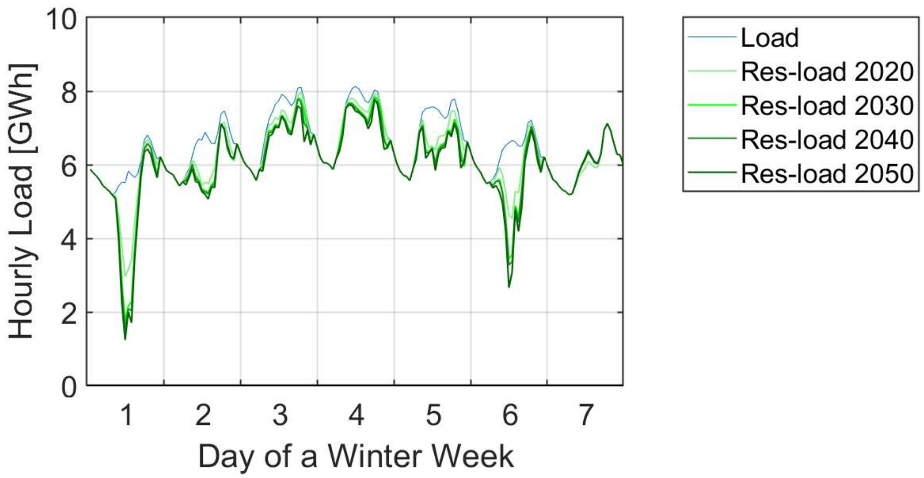


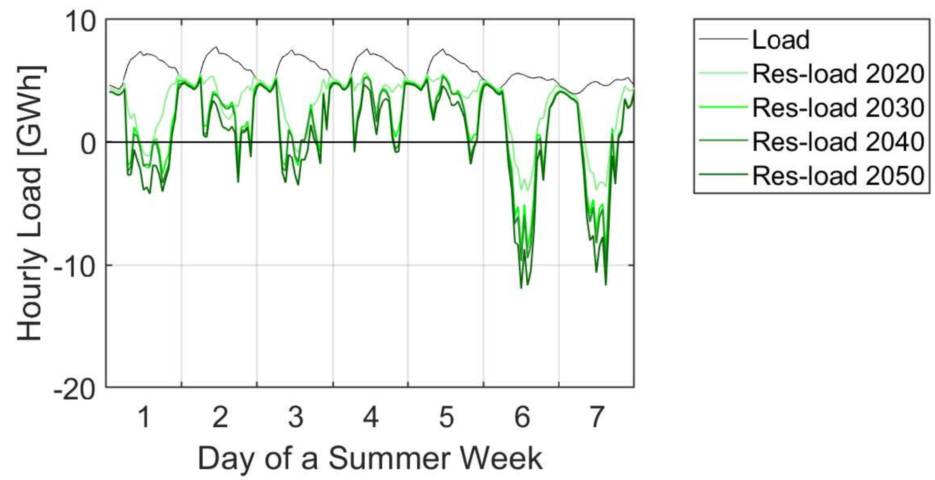
- Hourly residual load varies drastically from:
  - Day-to-day & hour-to-hour
- Phenomenon becomes more pronounced in summer and as PV penetration increases, i.e. residual load profiles deviate more and more from the original Swiss load profile over the years

- Exception on 7th day (i.e. Sunday) of the winter week
  - batteries installed to absorb the relatively lower PV generation in winter
  - load is supplied by the grid at the low retail electricity tariff available on Sunday
- Increasingly dynamic pattern of the hourly residual load emphasizes the need for flexibility resources

Dynamic Pattern of the Hourly Swiss Residual Load (15-year PBP)

The system's need for flexibility





- Hourly residual load varies drastically from:
  - Day-to-day & hour-to-hour
- Phenomenon becomes more pronounced in summer and as PV penetration increases, i.e. residual load profiles deviate more and more from the original Swiss load profile over the years

- Exception on 7th day (i.e. Sunday) of the winter week
  - batteries installed to absorb the relatively lower PV generation in winter
  - load is supplied by the grid at the low retail electricity tariff available on Sunday
- Increasingly dynamic pattern of the hourly residual load emphasizes the need for flexibility resources

Conclusions

- The combined PV plus battery system investments for some customer groups already yield a better net present value than PV alone today.
- The optimal PV and battery sizes increase over time mainly due to the projected cost reductions.
- The investment PBP fluctuates between 2020 and 2035 due to the mixed impacts of policy changes, cost and electricity price developments.
- Dynamics of new system load profiles caused by the seasonal, daily and hourly patterns of the solar generation emphasize the need for system flexibility.
- Investment decisions are highly sensitive to the expected payback periods, future costs, injection tariff developments, and wholesale and retail electricity price changes.

Limitation and Future Work

- Instead of synthetic load profiles, future work should include a bottom-up representation of electricity demand by utilizing realistic load patterns.
- We group the rooftop data using a limited number of clusters, a proper clustering method is required and a comprehensive analysis is needed to investigate the impact of the clustering.
- A future version should account for non-economic factors such as peer-effects and environmental considerations, etc.
- We model wholesale electricity price scenarios based on historical wholesale market, which cannot capture the price suppression effect of PV-battery system injections.
- A higher time resolution could be employed to enable a more granular assessment of operations and the economics for investing in PV-battery systems.

ETH zürich

THANK YOU!

Xuejiao Han

xuhan@ethz.ch

linkedin.com/in/xuejiao-han

References

[1] Bundesamt für Energie, “Energiestrategie 2050 [Online],” Available at: https://www.bfe.admin.ch/bfe/de/home/politik/energiestrategie- 2050.html, accessed on 2020-12-25.

[2] Bundesamt für Energie, “Schweizer Hausdächer und Hausfassaden könnten jährlich 67 TWh Solarstrom produzieren [Online],” Available at: https://www.bfe.admin.ch/bfe/de/home/news-und-medien/medienmitteilungen/mm-test.msg-id-74641.html, accessed on 2020-08-31.

[3] International Energy Agency, “Photovoltaic power systems programme annual report,” International Energy Agency, Tech. Rep., 2019.

[4] Swisssolar, “2.5 Gigawatt installierte Solarleistung: wir brauchen 20-mal mehr [Online],” Available at: https://www.swissolar.ch/services/medien/news/detail/n-n/25-gigawattinstallierte-solarleistung-wir-brauchen-20-mal-mehr/, accessed on 2020-08-31.

[5] Bundesamt für Energie, “Schweizerische Gesamtenergiestatistik 2019 [Online],” Available at: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.html, accessed on 2021-03-14.

[6] Bundesamt für Energie, “Berechnung von Potenzialen in Gemeinden [Online],” Available at: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/geoinformation/geodaten/solar/solarenergie-eignung-hausdach.html, accessed on 2020-06-23.