Welfare and Redistribution in Residential Electricity Markets with Solar Power

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Motivation - Reducing Emissions

- Governments worldwide aim at cutting fossil fuel emissions
- Solar PhotoVoltaic (PV) is one of the main renewables
  - In 2018 contributes to 2.6% of global demand and is 1^{st} electricity source in capacity deployed

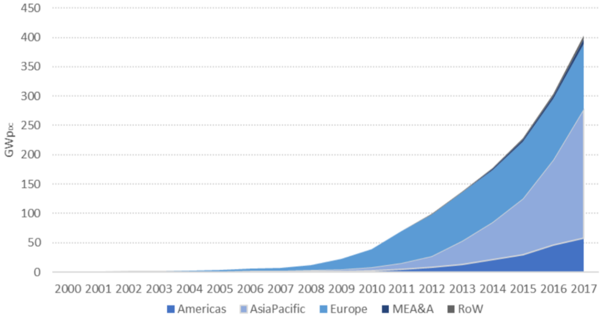
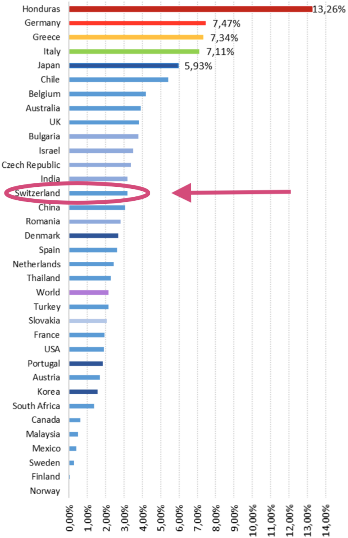


Figure: Evolution of regional PV installations (GW - DC)

Motivation - Reducing Emissions



Switzerland successful example (2017)

- 2.9GW installed PV capacity
- Over 3% of PV contribution to electricity demand
- 950 kWh/kWp average irradiation (same as Germany, Belgium,..)
- Capacity of ∼200W per habitant
  - 40% wrt Germany
  - 60% wrt Italy
  - 170% wrt Spain
  - 185% wrt France

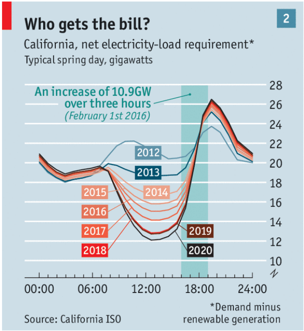
Motivation - Growth Drivers

Growth in solar PV installations mostly driven by

1. Government incentives
   - Direct: Feed-in tariffs (65%), installation cost subsidy (20%)
   - Indirect: Two-parts tariff for electricity bill
     - Consumption-based tariffs (cent per kWh) to finance energy costs, network costs, direct incentives
     - Fixed fees to finance network costs
2. Declining PV systems' prices
   - From $\sim$ 7 USD/W in 2001 to $\sim$ 0.3 USD/W in 2017

Motivation - Challenges from Growth in Solar PV

1. **Network Financing**: Households with PV need grid access
   - But contribute less to largely fixed network costs, increasing due to intermittency (doubled in South Australia since 2008)
   - Swiss regulator forecasts 0.68-1.4 CHF grid investment per kWh of new decentralized production in next 25-50 years



Economist.com

Motivation - Challenges from growth in solar PV

2. **Equity**: Richer households more likely to install PV, shifting the burden of network costs onto poorer households
   - More likely to own single house and afford installation costs
   - In our Swiss data the average income of households with a PV is 45% higher than the average income of those without
     - $\Rightarrow$ Income inequality in Switzerland is similar to EU countries, but wealth inequality is high and rising
3. **Cannibalization**: Solar PVs produce at zero marginal costs, driving down energy prices
   - Reduces incentive to adopt solar panels

Contribution

Address the challenges of **network financing** and **equity** using

- 2008-2013 yearly panel for 135k households in Bern (CH)
  - Data on electricity consumption, prices, income, wealth, demographics, PV adoption, building characteristics

1. Estimate a dynamic structural model of households' electricity consumption and PV adoption
   - Identify households' response to consumption-based tariffs, fixed fees, PV installation subsidies
   - Geographic RDD to address identification of tariffs and fees

Contribution

2. Counterfactual to quantify "death spiral" of tariff rise as PV adoptions increase over 10 years horizon, measuring
   - Regressive effect across PV owners & non-owners
   - Progressive effect across income distribution
3. Counterfactual with regulator's constrained optimization to find optimal tariff, fee, subsidy over 5 years horizon to
   - Achieve solar energy target (PV share of energy consumed)
   - Guarantee grid financing
   - Trade-off efficiency, equity, welfare motives

Literature

- **Electricity demand**: Reiss, White (2005), Ito (2014)
  - ⇒ Exact match of household income & wealth data
- **PV adoption**: Borenstein (2015), Burr (2014), De Groote, Verboven (2016), Langer, Lemoine (2018)
  - ⇒ First paper to combine energy consumption & PV adoption data, show how tariffs affect adoption
- **Distributional implications of environmental policies**: Wolak (2016), Reguant (2018)
  - ⇒ Income & wealth data allows us to make precise predictions
- **Network financing**: Borenstein (2008), Bushnell (2015)

Energy Market in Bern

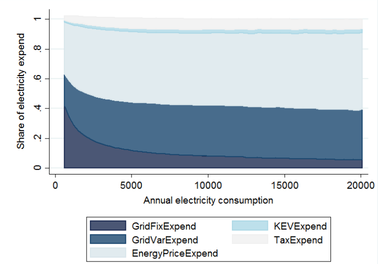
- Energy supply in Switzerland is decentralized to cantons
  - Utilities have local monopoly for distribution and retail
    - Owned by local government
    - Tariffs calculated based on long-term cost of production/import and transmission/distribution
- Providers in the Canton of Bern
  1. BKW Energie AG (200k households)
  2. Energie Wasser Bern (70k households)
  3. Energie Thun (20k households)

Households' Electricity Bill in Bern

1. Consumption-based tariffs
   - Energy price to cover electricity costs (P_E)
   - Grid price to cover network costs (P_G)
   - Taxes and price to finance renewables' subsidies (P_T)

   $\Rightarrow$ 2 providers offer uniform and double (night/day) tariffs, other provider only double tariff

2. Grid fixed fee to cover network costs (f)



Solar PV Incentives in Switzerland

Swiss government's 2020 target to cut fossil fuel use by 20%

- Direct support for PV installations since 2008
    - Until 2014: feed-in tariffs for 25 years & no own consumption
    - Since 2015: 30% installation cost subsidy & own consumption
    - Financed with consumption-based tariff for all households
- Indirect support for PV installations
    - 85% of average household's energy bill is consumption-based
    - Originally intended to encourage energy efficiency

The Dataset

Unique 2008-2013 yearly panel dataset for 135k households in the Canton of Bern, merging data from

1. Energy companies (BKW, EWB, ET)
   - Energy consumption and expenditure, PV installations, prices
2. Tax office of Bern
   - Income, wealth, and tax payments
3. Swiss Federal Statistical Office
   - Buildings' characteristics
4. Eturnity AG
   - Simulated PV production, installation costs, consumption profiles for all households

Simulated PV Data I

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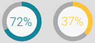
INDEPENDENCE AND OWN CONSUMPION



DEGREE OF INDEPENDENCE · OWN-CONSUMPTION

>> Seite 2

PAYBACK PERIOD

with battery
12,4 years
annual revenue: 1'383 CHF

without battery
14,7 years
annual revenue: 903 CHF

>> Seite 3

IINVESTMENT COST

One-time investment of
21'960 CHF

incl. Solar panel
incl. battery
incl. installation
incl. VAT
incl. subsidies

>> Seite 3

Your Heating System

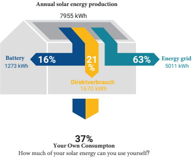
Heating:	Heating Pump
Warm Water:	Heating Pump
Consumption:	9'600 kWh
Alignment:	180°
Solar Panel:	8,12 kWp
Battery:	7 kWh
Annual Revenue:	7'955 kWh

>> Seite 5

INDEPENDENCE & OWN CONSUMPTION

SEITE 2

WHERE DOES MY ENERGY GO?



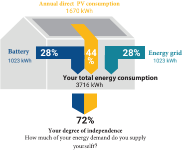
Why do I feed energy into the grid?

You feed your energy, apart from what you use directly, into your battery. As soon as the battery is full excess energy will be automatically fed into the grid.

WHERE DOES MY ENERGY COME FROM?

Why do I need energy from the grid?

Even if your solar pannel produces more energy in a year than your total annual consumption, and despite you battery, you might need to rely on energy from the grid during winter nights.



Simulated PV Data II

PROFITA-BILITY

«SOLARENERGIE LOHNT SICH FÜR SIE»

SEITE 3

INVESTMEN COSTS

Solar panel	23’578 CHF
Battery system	4’600 CHF
VAT 8%	2’254 CHF
Total exkl. VAT	28’178 CHF
Total inkl.VAT	30’432 CHF
Subsidy	-8’472 CHF
Your Investment	**21’960 CHF**
Expected tax deduction*	-3’294 CHF
Final costs	19’357 CHF

*Assumption marginal tax rate 15%

REVENUE

With battery

34’579 CHF

Without battery

22’579 CHF

Total savings from own consumption and revenue from selling ennergy, minus maintenance costs during the life time of solar panel/battery. No capital costs.

FUNDAMENTALS

Energy provider: CKW
Energy product: hydropower
PV-life span: 25 years
Inflation energy prices 2,1%
Maintenance PV: 1% Invest. p.a.
Capital cost: 1,0%
Maintenance battery 1.5% Invest.

INTEREST YIELD

Return of your capital/internal interest rate:

Only solar	with battery
2,44%	1,03%

Internal interest rate describes the average, yearly return of capital across the life-time of the PV, assuming the capital revenue is reinvested at the internal rate of interest.

PRODUCTION COSTS

1 kWh solar energy from your roof costs:

15,7 Rappen

Without battery cost, during the life-time of the solar panel incl. capital costs, incl. linvestment and maitenance.

CARBON FOOTPRINT

«EIN WICHTIGER BEITRAG FÜR DIE UMWELT»

SEITE 4

Your yearly **CO_2**-savings of **1’000 kg** are equivalent to

driving your car 8’132 km around the globe

reducing your carbon footprint by 15%

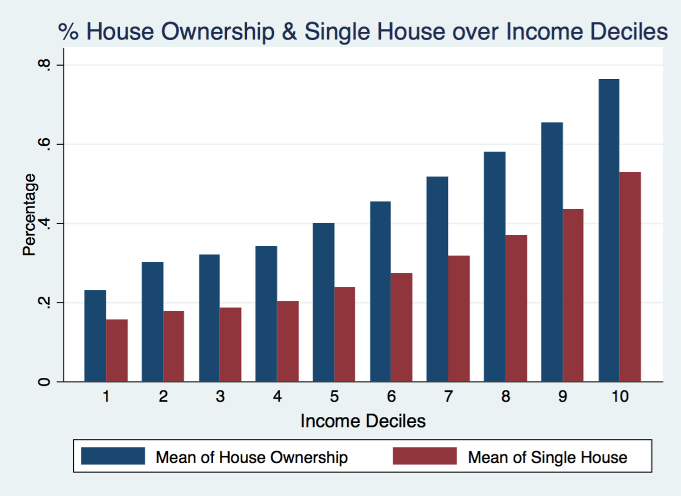
saving as much CO_2 as 80 trees consume during a year

Berechnungsgrundlagen: Der dargestellte Vergleich basiert auf einem Schweizer «Egal-Strommix».
Quellen: ESU-Services / BAFU: Treibhausgas-Emissionen der Schweizer Strommixe, 2012

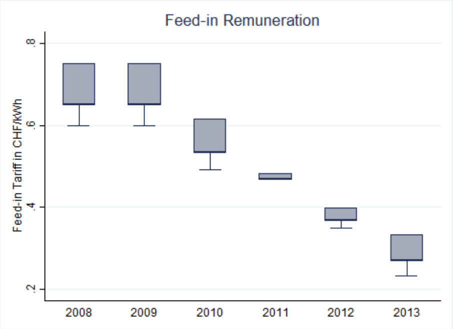
Descriptives

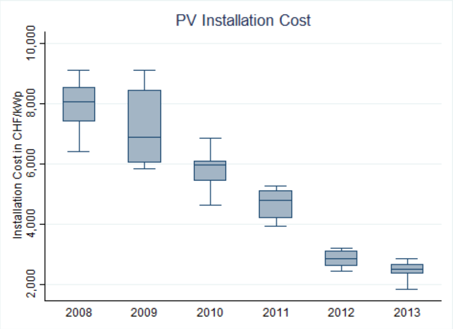
	N Obs	Mean	StdDev	Median
Energy Consumption (kWh)	657,750	**4,919**	5,189	3,293
Energy Expenditure (CHF)				
Total	657,750	**1,066**	917	793
Energy	657,750	477	461	338
Grid	657,750	497	358	396
Tax	657,750	71	88	44
KEV (Subsidy)	657,750	21	24	14
Income & Wealth (CHF)				
Total Income	657,750	95,225	128,644	80,179
Taxable Income	657,750	72,940	117,831	61,860
Total Wealth	657,750	529,660	2,053,701	248,283
PV Simulations				
Production Capacity (kW)	202,420	5.7	8.5	3.1
Production (kWh)	202,420	**9,431**	5,027	8,280
% Own Consumption	202,420	**15.7**	11.2	11.9
% Autonomy	202,420	**42.5**	14.1	39.4

Richer Households More Likely to Adopt PV



Dynamic Trade-off in PV Adoption





Household's Problem I

Household $i = 1, ..., N$ decides every period $t = 1, ..., \infty$

- Energy consumption in kWh $c_{it} > 0$
- Outside good consumption $q_{it} \geq 0$
- Solar panel adoption $\mathcal{PV}_{it} = \{0, 1\}$ (absorbing state)

$$\mathcal{PV}_{it} = \begin{cases} 1, & \text{install the solar panel} \\ 0, & \text{don't install the solar panel} \end{cases}$$

- Subject to the budget constraint

$$P_{ut} c_{it} + q_{it} + f_{ut} \leq I_{it} + \tau_t Y_{it}$$

  - P_{ut}, f_{ut} are electricity price and fixed fee charged by utility u
  - I_{it} is household's income, Y_{it} is PV production, τ_t feed-in tariff

Household's Problem II

Household's non-regenerative optimal stopping problem

$$V(S_1) = \max_{c(S_t), q(S_t), \mathcal{PV}(S_t)} \sum_{t=1}^{\infty} \rho^{t-1} E\left[u(c_t, q_t, \mathcal{PV}_t, S_t; \Lambda) - C(\mathcal{PV}_t, S_t; \theta) + \varepsilon(\mathcal{PV}_t) \middle| S_1 \right]$$

$$\text{s.t. } c_t > 0, \quad q_t \geq 0, \quad P_t c_t + q_t + f_t \leq I_t + \tau_t Y_t$$

- $u(.; \Lambda)$ is utility from c_t, q_t
- $C(.; \theta)$ is cost to install solar panel
- $\rho > 0$ is discount factor, $\varepsilon(\mathcal{PV}_t)$ are T1EV shocks
- Λ, θ are the structural parameters we want to estimate
- S_t are state variables $(P_t, f_t, \tau_t, I_t, Y_t)$

Estimating the Model

Estimate household's model in 3 steps (Handel, Nevo, 2006)

1. Static utility maximization to choose optimal electricity consumption, conditional on PV
   - $\Rightarrow$ Parameters of electricity demand with geographic RDD
2. Expectation over evolution of state variables that determine dynamic PV adoption decision
   - $\Rightarrow$ Parameters of transition probabilities
3. Dynamic utility maximization to adopt PV
   - $\Rightarrow$ Parameter of installation cost function

Step 1 - Energy Demand

1. Optimal electricity consumption, conditional on PV

$$c_{it}(\mathcal{PV}_{it}, S_{it}; \Lambda) = \begin{cases} {P_{ut}}^{\beta}(I_{it} - f_{ut} + \tau_t Y_{it})^{\gamma} e^{\alpha + X'_{it}\omega + \nu_{it}} & \text{if } \mathcal{PV}_{it} = 1 \\ {P_{ut}}^{\beta}(I_{it} - f_{ut})^{\gamma} e^{\alpha + X'_{it}\omega + \nu_{it}} & \text{if } \mathcal{PV}_{it} = 0 \end{cases}$$

- $u \in \{BKW, EWB, ET\}$ are the three utilities
- X_{it} are household/building characteristics, ν_{it} are shocks
- Parameters of demand function $\Lambda = \{\alpha, \beta, \gamma, \omega\}$ from

$$\ln(c_{it}) = \alpha + \beta \ln(P_{ut}) + \gamma \ln(I_{it} - f_{ut} + \tau_t Y_{it}) + X'_{it}\omega + \nu_{it}$$

Step 1 - Energy Demand

- Use $\widehat{\Lambda}$ to compute indirect utilities

$$v_{it}(\mathcal{PV}_{it}, S_{it}; \widehat{\Lambda}) = \begin{cases} I_{it} - f_{ut} + \tau_t Y_{it} - \frac{1}{\widehat{\beta}+1} P_{ut} \widehat{c}_{it}^1 & \text{if } \mathcal{PV}_{it} = 1 \\ I_{it} - f_{ut} - \frac{1}{\widehat{\beta}+1} P_{ut} \widehat{c}_{it}^0 & \text{if } \mathcal{PV}_{it} = 0 \end{cases}$$

  - $\widehat{c}_{it}^1, \widehat{c}_{it}^0$ are predicted energy consumptions with and without PV

- Assume households keep track of v_{it}^1, v_{it}^0 (Handel, Nevo, 2006)
  - Form expectations over evolution of

$$v_{it}^{1R} = \tau_t Y_{it}, \qquad v_{it}^{1C} = -\frac{1}{\widehat{\beta}+1} P_{ut} \widehat{c}_{it}^1, \qquad v_{it}^0 = -\frac{1}{\widehat{\beta}+1} P_{ut} \widehat{c}_{it}^0$$

- Let PV installation cost function $C\left(\mathcal{PV}_{it}, S_{it}; \theta\right) = \theta_F F_{it} + \theta_{Fsq} F_{it}^2$

Step 2 - Transition Probabilities

2. Expectation over evolution of state variables
   - Let v^{1R}, v^{1C}, v^0, F follow an AR(1), estimate $\delta_{v1R}, \delta_{v1C}, \delta_{v0}, \delta_F$
   - Installing is absorbing state, use $\widehat{\delta}_{v1C}$ to compute PDV of future utilities from adopting

$$PDV_{it} = \overbrace{\sum_{s=1}^{25} \rho^s (1-\zeta)^s \tau_t Y_{it}}^{\text{Feed-in period}} + \overbrace{\sum_{s=26}^{\infty} \rho^s (1-\zeta)^s \widehat{\delta}^s_{v1C} P_{ut} Y_{it}}^{\text{Post feed-in period}} + \sum_{s=1}^{\infty} \rho^s \widehat{\delta}^s_{v1C} [-\frac{1}{\widehat{\beta}+1} P_{ut} \widehat{c}^1_{it}]$$

   - ζ is PV's degrade factor, ρ from De Groote, Verboven (2016)
   - Assume conditional independence

$$p(\widetilde{S}', \varepsilon' | \widetilde{S}, \varepsilon; \delta, \lambda) = p_1(\widetilde{S}' | \widetilde{S}; \delta) p_2(\varepsilon' | \widetilde{S}'; \lambda)$$

Step 3 - PV Adoption

3. Dynamic utility maximization to adopt PV
   - Bellman equation of simplified non-regenerative problem

$$V(\widetilde{S}_t) = \max_{\mathcal{PV}_t} \left\{ v_t(\mathcal{PV}_t) + \varepsilon(\mathcal{PV}_t) + \mathcal{PV}_t \left(PDV_t - \theta_F F_t - \theta_{Fsq} F^2 \right) + (1 - \mathcal{PV}_t) \rho E \left[V(\widetilde{S}_{t+1} | \widetilde{S}_t) \right] \right\}$$

   - Alternative specific expected value functions

$$\mathrm{EV}(\widetilde{S}, \mathcal{PV}) = \begin{cases} \theta_v v(1) + \theta_v PDV - \theta_F F - \theta_{Fsq} F^2 + \varepsilon(1) & \text{if } \mathcal{PV} = 1 \\ \theta_v v(0) + \varepsilon(0) + \rho \int_{\widetilde{S}'} \mathrm{EV}(\widetilde{S}') p_1(\widetilde{S}' | \widetilde{S}; \widehat{\delta}) & \text{if } \mathcal{PV} = 0 \end{cases}$$

   - Recover θ by maximum likelihood with NFXP

Energy Demand - Identification

$$\ln(c_{it}) = \alpha + \beta \ln(P_{ut}) + \gamma \ln(I_{it} - f_{ut} + \tau_t Y_{it}) + X_{it}'\omega + \nu_{it}$$

We face three identification challenges for β, γ

1. Uniform vs double (night/day) tariffs
   - Selection: Households assigned to uniform/double depending on whether building has heat pump and double tariff meter

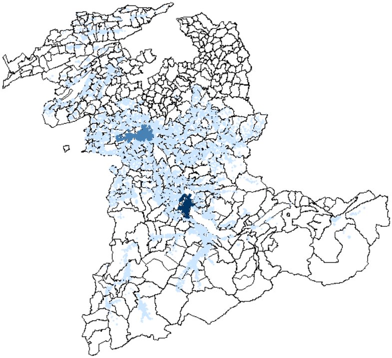
     $\Rightarrow$ Observe switching only among movers, take building characteristics as exogenous
   - Endogeneity: Double tariff households can change their marginal price adjusting day/night consumption shares

     $\Rightarrow$ Predict consumption shares based on demographics and use these to construct marginal price
2. Current vs lagged tariffs/fees

   $\Rightarrow$ Find that respond to lagged (Ito, 2014)

Energy Demand - Identification

3. Simultaneity in demand vs supply
   - Geographic RDD exploiting price variation between companies (Black, 1999, Ito, 2014)
     - ⇒ Assign households to common border points (1km distance) and include border point fixed effects



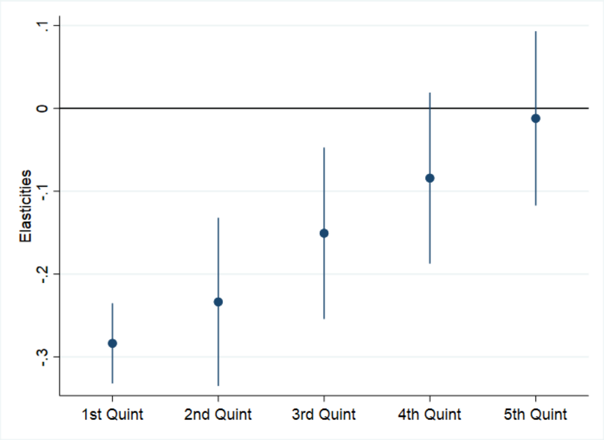
Results - Energy Demand

Variables	(1)	(2)	(3)	(4)	(5)
Price (P_{ut-1})	-.92***	-.10***	-.07***	-.18***	-.16***
	(0.01)	(0.02)	(0.01)	(0.03)	(0.03)
Income ($I_{it} - f_{ut-1}$)	0.00	0.01**	0.01**	0.01	0.01*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Wealth	-0.01***	-0.01***	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Home Owner	0.14***	0.11***	0.11***	0.06***	0.07***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
Number of Rooms	0.14***	0.09***	0.09***	0.12***	0.11***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Number of Rooms Sq	-0.01***	-0.01***	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Apartment Surface	0.11***	0.11***	0.12***	0.14***	0.14***
	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
Double Tariff BKW/EWB		.43***		.41***	.41***
		(0.00)		(0.01)	(0.01)
Double Tariff ET		.14***		.24***	.24***
		(0.01)		(0.01)	(0.02)
Share Day/Night Decile FE	No	No	Yes	No	No
Household Size FE	Yes	Yes	Yes	Yes	Yes
Household Age FE	Yes	Yes	Yes	Yes	Yes
Heating System FE	Yes	Yes	Yes	Yes	Yes
Water System FE	Yes	Yes	Yes	Yes	Yes
Apartment No. FE	Yes	Yes	Yes	Yes	Yes
Construction Period FE	Yes	Yes	Yes	Yes	Yes
Non-Positive Income/Wealth FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Border FE	No	No	No	No	Yes
N Obs	459,466	459,466	459,466	89,165	89,165
R^2	0.553	0.582	0.588	0.584	0.587

Results Energy Demand - Heterogeneity

Elasticities across the income distribution

⇒ High income quintiles less elastic



Results Transition Probabilities & PV Adoption

Parameters	
δ_{v0}	.99***
	(0.00)
δ_{v1R}	.82***
	(0.00)
δ_{v1C}	.99***
	(0.00)
δ_{F}	.76***
	(0.00)
θ_{F}	.06***
	(0.03)
θ_{Fsq}	-.00
	(0.00)
N Obs	52,705

- $\delta_{v1R} < 1 \Rightarrow$ indirect utility from adoption declining over time
  - $\Rightarrow$ Due to feed-in tariff reducing over time
- $\delta_{F} < 1 \Rightarrow$ installation costs declining over time
- $\theta_{F} > 0 \Rightarrow$ PV adoption decreasing in installation costs

Counterfactual Simulations for BKW from 2013

1. **Death spiral**: Simulate 10 years path of PV adoptions
    - Increase in grid tariff to recover grid costs up to 14%
    - Quantify regressive (PV owners vs non-owners) and progressive (income deciles) effects

2. **Tariff design**: Set variable/fixed tariffs and subsidy to
    - Achieve 7%-9% solar energy targets
        - ⇒ 9% as benchmark case of solar fully accounting for Swiss 2020 renewable energy target
    - Recover network costs, increasing due to grid adjustments
    - Trade-off efficiency, equity, and welfare motives

Counterfactual Simulation

- Define BKW's baseline grid costs GC_0 (with no PVs) as

$$GC_0 = N f_0 + \sum_{i}^{N} \bar{c}_i P_{G0}$$

  - To be recovered under each counterfactual, plus 0.055 CHF per kWh of PV energy production per year
    - Swiss regulator's 2035 budget of renewables' grid costs

- Define a household's grid expenditure $GE_{it}(P_{Gt}, f_t, s)$ as

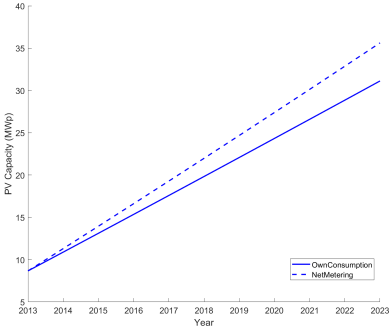
$$GE_{it}(P_{Gt}, f_t, s) = f_t + P_{Gt}\Big[\big(\hat{c}^1_{it}(P_{Gt}, f_t) - OC_i Y_{it}\big) * \Pr(\mathcal{PV}_{it} = 1 | P_{Gt}, f_t, s) + \hat{c}^0_{it}(P_{Gt}, f_t) * (1 - \Pr(\mathcal{PV}_{it} = 1 | P_{Gt}, f_t, s)) \Big]$$

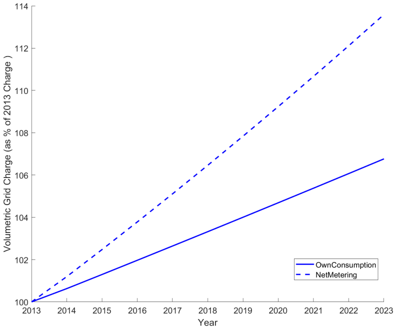
  - OC_i is household's own consumption from PV

Counterfactual 1 - Death Spiral

Change in **PV capacity** and **grid tariff** P_{Gt} with 10 yrs adoptions

- *Own Consumption*: Adopters save on grid expenditure consuming 15% of their own production
- *Net Metering*: Adopters subtract 100% of energy produced from electricity bill (like having battery)

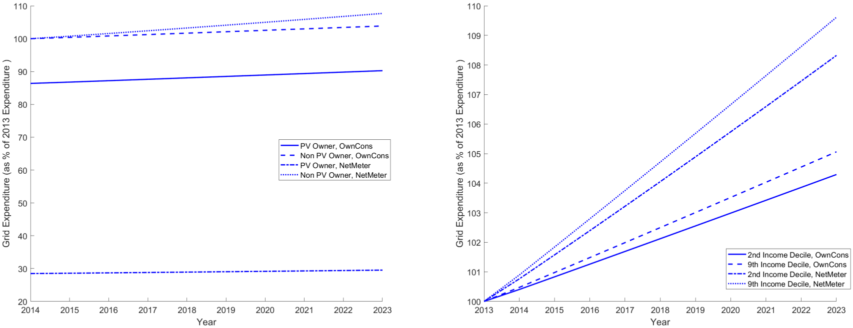




Counterfactual 1 - Death Spiral

Change in **PV capacity** and **grid tariff** P_{Gt} with 10 yrs adoptions

- **Regressive** effect: Adopters save 13%-71% on grid expenditure
- **Progressive** effect: High income contribute more to grid costs as are less price sensitive



Counterfactual 2 - Regulator's Problem

- Solve 3 alternative regulator's problems with respect to grid tariff (P_G), fixed fee (f), subsidy (s) defined as
  - *Optimal* solution, **maximize** households' aggregate **welfare**
  - *Efficient* solution, **minimize** households' grid **expenditure**
  - *Equitable* solution, **minimize difference** between **counterfactual** and **baseline** households' grid **expenditure**
- Under solar energy target and network financing constraints

Counterfactual 2 - Regulator's Problem

Equitable solution implies solving following constrained problem

$$\min_{P_G, f, s} \sum_{i}^{N} \frac{\left[\sum_{t=1}^{5} (GE_{it}(P_G, f) - GE_{i0})\right]^2}{I_{it}}$$

$$s.t. \quad \frac{\sum_i Y_i \Pr(\mathcal{PV}_{i5} = 1 | P_G, f, s)}{\sum_i \widehat{c}_{i5}(\mathcal{PV}_i, P_G, f)} \geq SET \qquad \text{(solar energy target)}$$

$$s.t. \quad \sum_{t=1}^{5} \left[GC_0 + \sum_i \Pr(\mathcal{PV}_{it}^{new} = 1 | P_G, f, s) \left(sF_{it} + 0.055 Y_{it} \right) \right]$$

$$= \sum_{t=1}^{5} \sum_{i=1}^{N} GE_{it}(P_G, f) \qquad \text{(network financing)}$$

Counterfactual 2 - Tariff Design

	Solar Energy Target								
	7.8%			8.4%			9.0%		
	Eff	Equ	Opt	Eff	Equ	Opt	Eff	Equ	Opt
Instruments									
Price (P_G) Change	43.4	5.1	-55.9	47.3	6.1	-47.2	50.7	9.0	-41.4
Fixed Fee (f) Change	-97.3	7.4	182.6	-99.2	13.6	166.3	-99.2	15.0	159.2
Subsidy (s) as % F_i	16.80	23.60	36.20	37.2	43.8	53.8	54.6	60.8	69.4
% Change GE_i by Income									
1^{st} decile	-10.0	4.9	28.3	-8.6	7.6	28.3	-6.8	9.7	29.5
2^{nd} decile	-11.6	4.9	30.9	-10.2	7.6	30.6	-8.5	9.7	31.6
3^{rd} decile	-9.7	4.9	28.1	-8.2	7.6	28.1	-6.4	9.8	29.3
4^{th} decile	-7.9	4.9	25.4	-6.3	7.5	25.6	-4.4	9.7	27.0
5^{th} decile	-4.3	4.9	20.0	-2.6	7.4	20.8	-0.6	9.7	22.4
6^{th} decile	-1.6	4.9	15.8	0.3	7.3	17.0	2.4	9.6	18.8
7^{th} decile	1.6	4.8	10.9	3.6	7.2	12.6	5.9	9.6	14.7
8^{th} decile	4.2	4.8	6.9	6.3	7.1	9.0	8.7	9.5	11.3
9^{th} decile	7.5	4.8	2.1	9.8	7.0	4.6	12.3	9.4	7.2
10^{th} decile	11.1	4.7	-3.9	13.6	6.7	-0.8	16.1	9.2	2.1
% Change GE_i by PV									
Adopting PV	-16.8	-10.6	-0.5	-15.2	-8.5	0.5	-13.4	-6.6	2.0
Not Adopting PV	4.4	4.9	6.0	6.5	7.2	8.3	8.8	9.6	10.7
Welfare Change									
CHF Per Household	-21.1	-16.3	-12.8	-31.3	-26.5	-23.7	-42.1	-37.5	-35.1
% of 2013 Welfare	-0.03	-0.03	-0.02	-0.05	-0.04	-0.04	-0.07	-0.06	-0.06
CHF per kWh Solar Energy	0.11	0.13	0.17	0.17	0.19	0.22	0.23	0.25	0.27

Conclusion

- We proposed alternative tariff schemes for the residential energy market of the Canton of Bern
- We address two issues posed by the growing number of PV installations: network financing and equity
- We recover optimal tariffs through a regulator's optimization problem, based on models of energy demand and PV adoption
- We find alternative combinations of grid tariff, grid fee, and PV subsidy to achieve renewable energy targets