Welfare and redistribution in residential electricity markets with solar power

Feger et al. (2022), RES.

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Motivation

- Increasing adoption of residential solar panels Challenge regulators: network financing and vertical equity.
    - Grid costs are paid by consumption-based marginal retail price.
    - Adopters are usually wealthier households. Regressive residtrivutive effect in green energy incentives $\Rightarrow$ subsidy received by richer households.
- **Question: Should grid financing be based on consumption or fixed?** Rich households share the same burden as poorer households. But it may reduce the incentive to adopt solar panels, and it might increase grid expenditure relatively more for low-consumption households.

Results Preview

Marginal cost is more cost-efficient and progressive to incentivize PV adoption as rich households consume more and are less price sensitive. But it also causes a larger welfare loss.

Remuneration

- 2008-2013: subsidized feed-in tariff
- 2014 onwards: Self-consumption and feed-in tariff

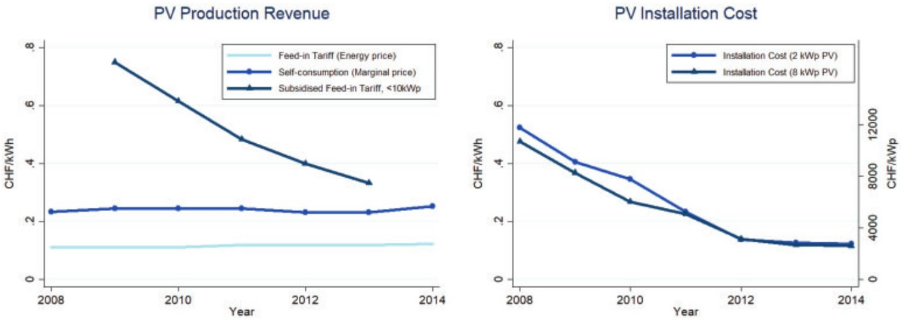

FIGURE 1

Feed-In Remuneration and Average Installation Cost

Data

- 165,000 households in Canton of Bern, Switzerland (2008-2014)
- Variables:
  - Energy Companies: Energy consumption, expenditures, electricity price, solar panel installations;
  - Admin Data: income, wealth, building characteristics;
  - Energy Advisory Platform: simulation for potential energy production and self-consumption.

Price Breakdown

TABLE 1
Annual energy prices, network tariffs, and taxes

	BKW		EWB		ET	
	Mean	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Fixed fee (CHF/year)	139	27	82	47	105	20
Marginal price (Rp./kWh)	21	2.8	17.5	2.3	22.5	1.6
Energy price	10.3	1.2	10	0.8	11.5	.5
Grid price	8.3	1.7	6.4	1.6	8.2	1.8
Municipality tax	1.8	0.3	0.5	0.3	2.3	1.6
KEV tariff	0.5	0.1	0.5	0.2	0.5	0.1

Notes: The table shows average annual prices and standard deviation in the sample. KEV Tariff is the surcharge used to promote renewable energy. Rp (Rappen) is one-hundredth of a Swiss franc (CHF). All prices include the value-added tax.

Households Quintiles

Table A.1: Energy and Household Characteristics by Income Quintile

Variables	1^{st} <36k	2^{nd} 36k-54k	3^{rd} 54k-72k	4^{th} 72k-99k	5^{th} >99k
Energy Consumption (kWh)					
Mean	2,971	3,367	3,959	4,606	5,777
Standard Deviation	2,984	3,364	3,539	3,769	4,501
Energy Expenditure (CHF)					
Mean	696	777	895	1,023	1,248
Standard Deviation	557	620	645	682	829
Energy Price Expenditure (CHF)	296	333	391	455	569
Grid Expenditure (CHF)	346	380	428	480	570
Share of Fixed Fee (%)	39.8	38.1	34.3	31.2	27.4
Income Share Energy (%)	3.9	2	1.7	1.4	1.1
Home Ownership (%)	17	29	40	54	72
Married (%)	16	31	53	70	80
Age HH Head	54.9	54.1	54.3	54.4	54.9
Householdsize	1.3	1.6	2	2.3	2.6
PV Installation (%)	.08	.17	.33	.7	1.61
Heating System (%)					
Electric	4	4	4	4	4
Heat Pump	2	3	5	7	9
Oil/Gas/Coal	94	93	91	89	87

Simulated Energy Production

TABLE 5
Simulated annual capacity and energy production

	N Obs	Mean	Std Dev	5th Perc	Median	95th Perc
PV production capacity (kWp)	40,394	9.5	4.7	4.7	8.4	18.9
PV energy production (kWh)	40,394	9,687	5,586	4,708	8,355	19,116
Self-consumption						
% of production	40,381	14.8	10.1	5.1	12.4	33.8
% of consumption	40,394	20.3	8.1	11.8	18.6	33.4
in kWh	40,394	1,223	876	592	990	2,626

Notes: The variables show simulated capacity and potential energy production for homeowners of single or double apartment buildings assigned to BKW. This is the subset of households that, in our PV adoption model, will be allowed to choose whether to install a solar panel or not. Values are simulated based on roof size, appliances, and geographic location. The number of observations equals the number of households. kWp means kilowatt peak, which is the capacity of a solar panel under standard test conditions.

Assumptions

- Consumers respond to 1-year lagged average electricity price.
- Subsidized feed-in tariff and solar panel prices both decrease over time.
- Solar adoption does not affect electricity price and consumption level.

Setup

- household $i = 1, ..., N$ decides every year $t = 1, ...\infty$ electricity consumption C_{it}, other good Q_{it} and solar panel adoption $PV_{it} = \{0, 1\}$.
- Energy demand function:

$$C_{it} = P_{ut}^{\beta_i} \cdot e^{\alpha + X_{it}' \omega + \nu_{it}} \tag{1}$$

P_{ut}: electricity price, X_{it}: household characteristics, ν_{it}: idiosyncratic shock.

Household's Problem I

1. Indirect utility without solar panel:

$$v_{it}(PV_{it} = 0) = \tilde{I}_{it} - F_{ut} - \frac{1}{\hat{\beta}_i + 1} P_{ut} C_{it} \tag{2}$$

2. Indirect utility with solar panel:

$$v_{it}(PV_{it} = 1) = \tilde{I}_{it} - F_{ut} - \frac{1}{\hat{\beta}_i + 1} P_{ut} C_{it} + R_{it} \tag{3}$$

Household's Problem II

3. R_{it}: remuneration from self-consumption and feed-in tariff.

$$\begin{aligned} R_{it}^{FT} &= \sum_{s=t}^{t+24} \rho^{s-t}(1-\xi)^{s-t} \cdot \tau_{it} \cdot Y_i + \rho^{25} R_{t+25}^{SC} \\ R_{it}^{SC} &= \sum_{s=t}^{\infty} \rho^{s-t}(1-\xi)^{s-t} \cdot Y_i \cdot [SC_i \cdot E[P_{ut}] + (1-SC_i) \cdot E[P_{ut}^{e}]] \end{aligned} \tag{4}$$

$E[P_{ut}]$: average electricity price, $E[P_{ut}^{e}]$: average feed-in tariff price, SC_i: self-consumption rate (exogenous).

Household's Problem III

4. F_{it}: solar panel installation cost:

$$F_{it} = (1-S)(1-T_i) \cdot kWp_i \cdot C_t^{kWp} \tag{5}$$

T_i: marginal income tax rate, S: subsidy rate, 30%.

5. Optimal stopping model subject to yearly budget constraint:

$$\mathcal{V}_i(\mathcal{S}_{it}) = \max_{PV_{it}} \{\theta_v v_{it}(PV_{it}) + \varepsilon_{it}(PV_{it}) + PV_{it}(\theta_v V_{it} + \theta_{F_i} F_{it}) + (1-PV_{it})\rho E[\mathcal{V}_i(\mathcal{S}_{it+1}|\mathcal{S}_{it}])\} \tag{6}$$

V_{it}: presented value of future utility, ε_{it}: type I extreme value shock.
Parameter θ_v and θ_{F_i} are going to be estimated.

6. $\mathcal{S}_{it} = \{R_{it}, F_{it}\}$: state variable, follow AR(1) process.

Household's Problem IV

7. normalize $v_{it}(PV_{it}=0)=\mu$, **consumption and adoption are independent**. Then the probability of adoption is:

$$Pr(PV_{it}=1|\mathcal{S}_{it}) = \frac{exp[\theta_v R_{it} + \theta_{Fi} F_{it}]}{exp[\theta_v R_{it} + \theta_{Fi} F_{it}] + exp[\rho \int_{\mathcal{S}_{it+1}} E[\mathcal{V}_i(\mathcal{S}_{it+1}|\mathcal{S}_{it})] p_1(\mathcal{S}_{it+1}|\mathcal{S}_{it})]} \quad (7)$$

$p_1(\mathcal{S}_{it+1}|\mathcal{S}_{it})$ is the transition probability of state variable.

Estimation Methodology

- Energy demand function:

$$\ln(C_{it}) = \alpha + \beta_i \ln(P_{ut-1}) + \alpha + X'_{it}\omega + \underbrace{\mu_t + \xi_b + \tilde{v}_{it}}_{v_{it}} \tag{8}$$

μ_t: time fixed effect, ξ_b: border fixed effect.

- Adoption probability: Log-likelihood maximization:

$$L(\theta_v, \theta_{Fi}) = \sum_{i=1}^{N}\sum_{t=1}^{T}\{PV_{it}\ln(Pr(PV_{it}=1|\mathcal{S}_{it})) + [1-PV_{it}]\ln(1-Pr(PV_{it}=1|\mathcal{S}_{it}))\} \tag{9}$$

Demand Elasticity

TABLE 6
Energy price elasticities

Variables	(1)	(2)
Price	−0.166***	−0.224***
	(0.014)	(0.030)
Price interactions		
2nd wealth quintile	0.063***	0.072***
	(0.003)	(0.005)
3rd wealth quintile	0.092***	0.099***
	(0.003)	(0.005)
4th wealth quintile	0.103***	0.129***
	(0.003)	(0.006)
5th wealth quintile	0.085***	0.115***
	(0.003)	(0.007)
Double tariff BKW/EWB	0.457***	0.433***
	(0.004)	(0.010)
Double tariff ET	0.155***	0.267***
	(0.005)	(0.019)

Transition Process

TABLE 7
AR(1) estimates

	(1)	(2)	(3)
δ_{FT}	0.873***		
	(0.000)		
δ_{SC}		1.016***	
		(0.000)	
$\delta_{\mathcal{F}}$			0.774***
			(0.000)
N Obs	204,979	204,979	204,979
R^2	0.965	0.994	0.950
$\hat{\sigma}$	0.390	0.039	0.444

Adoption Results

TABLE 8
PV adoption results

Parameters	(1)	(2)	(3)
θ_v	0.231***	0.213***	0.214***
	(0.020)	(0.019)	(0.019)
$\theta_{\mathcal{F}}$	−0.452***	−0.569***	−0.702***
	(0.020)	(0.040)	(0.058)
Fixed cost interactions			
2nd wealth quintile		0.067	0.148
		(0.094)	(0.108)
3rd Wealth quintile		0.044	0.125
		(0.068)	(0.082)
4th wealth quintile		0.150***	0.251***
		(0.048)	(0.064)
5th wealth quintile		0.239***	0.357***
		(0.049)	(0.066)
Year 2010			−1.096***
			(0.153)
Mid-age household head			0.310***
			(0.050)
Rural area			0.210***
			(0.053)
N Obs	204,979	204,979	204,979
LR test statistic	263.9	351.6	506.0

Regulator's Problem I

- constraints:
  1. Solar Energy Target
  2. Fixed Grid Investment Costs
- Stimulus:
  1. Upfront cost subsidy
  2. Self consumption
- Alternative policys:
  1. Subsidy: additional source of financing
  2. Marginal price increase: more incentive, additional grid revenue, lower consumption

Regulator's Problem II

3. Fixed price: lower incentive, fixed fee increases comparably more for low-consumption households.

- Network financing:

$$GE_{it}(P_{Gt},F_t) = F_t + P_{Gt}\cdot[P^t_{\beta_i}e^{X'_{it}\omega} + \nu_{it} - SC_i\cdot Y_{it}\cdot Pr(PV_{it}=1|P_{Gt},F_t,S)] \tag{10}$$

$$\sum_{i=1}^{N} GE_{it}(P_{Gt},F_t) = GC_0 + \sum_{i=1}^{N} Pr(PV_{it}=1|P_{Gt},F_t,S)\cdot[0.055(1-SC_i)Y_{it} + SF_{it}] \tag{11}$$

GC_0: fixed grid investment cost, SF_{it}: solar panel subsidy. additional grid cost of CHF 0.055 per kWh for non-self-consumed electricity.

Regulator's Problem III

- Solar Energy Target:

$$\frac{\sum_i Y_{it} Pr(PV_{it} = 1 | P_{Gt}, F_t, S)}{\sum_i \hat{c}_{it}(PV_{it}, P_{Gt}, F_t)} \geq SET \tag{12}$$

$\hat{c}_{it}$: net consumption.

Objective Function

Objective functions:

	No equity	Equity
Cost	$\min_{P_G,F,S} \sum_i \sum_{t=1}^5 GE_{it}(P_G,F)$	$\min_{P_G,F,S} \sum_i \frac{\left[\sum_{t=1}^5 (GE_{it}(P_G,F) - GE_{i0})\right]^2}{I_{it}}$
Welfare	$\max_{P_G,F,S} \sum_i \sum_{t=1}^5 v_{it}(P_G,F)$	$\min_{P_G,F,S} \sum_i \frac{\left[\sum_{t=1}^5 (v_{it}(P_G,F) - v_{i0})\right]^2}{I_{it}}$

Constraints:

$$\begin{aligned}
&\sum_{t=1}^{5}\sum_{i=1}^{N} GE_{it}(P_G,F) \\
&\quad = \sum_{t=1}^{5}\left[GC_0 + \sum_{i=1}^{N} \Pr(\mathcal{PV}_{it}^{\text{new}} = 1 | P_G,F,S)\big(0.055(1-\mathcal{SC}_i)\widetilde{Y}_{it} + \mathcal{SF}_{it}\big)\right] && \text{(network financing)} \\
&\frac{\sum_i Y_{i5} \Pr(\mathcal{PV}_{i5} = 1 | P_G,F,S)}{\sum_i \widehat{c}_{i5}(\mathcal{PV}_{i5},P_G,F)} \geq SET && \text{(solar energy target),}
\end{aligned} \tag{18}$$

Counterfactual Results

TABLE 10

% change in marginal grid price, fee, subsidy, grid expenditure, welfare

	Solar energy target							
	Status quo (7.5%)				**Swiss regulator (9.0%)**			
	Cost	Cost equity	Welf	Welf equity	Cost	Cost equity	Welf	Welf equity
Instruments								
% Grid price (P_G) change	25.8	−4.4	−69.8	−13.2	34.6	−0.7	−30.8	−10.7
% Fixed fee (f) change	−96.3	10.8	257.3	42.7	−98.5	27.0	138.8	63.9
% subsidy (s) as % F_i	20.8	29.0	50.0	31.5	83.3	91.0	98.3	93.5
% Marginal price change	11.5	−2.0	−31.2	-5.9	15.4	−0.3	−13.8	−4.8
PV adoption (%)	1.8	1.9	2.0	1.9	2.4	2.4	2.5	2.4
Percentage change by income quintile of grid expenditure (GE_i)								
1st quintile	−15.5	4.2	49.6	10.1	−11.0	12.4	33.2	19.3
2nd quintile	−12.0	3.9	40.9	8.7	−7.2	11.7	28.7	17.3
3rd quintile	−7.1	3.5	28.0	6.6	−1.8	10.8	22.1	14.5
4th quintile	−2.9	3.1	17.2	4.9	2.7	10.0	16.6	12.2
5th quintile	1.8	2.6	5.0	2.9	7.8	9.0	10.3	9.4
Percentage change by PV ownership of grid expenditure (GE_i)								
Non-PV HH	2.4	2.9	4.4	3.1	8.5	9.4	10.3	9.7
PV HH	−19.5	−13.7	−0.8	−12.0	−14.9	−7.9	−1.7	−5.8
Agg. welfare change (M CHF)	−12.16	−11.60	−11.02	−11.46	−14.76	−14.21	−13.93	−14.10
Grid integr. cost (M CHF)	2.24	2.34	2.62	2.37	3.29	3.44	3.59	3.49
Subsidy cost (CHF per kWh)	0.09	0.13	0.24	0.15	0.45	0.50	0.55	0.51

Distributional Effects

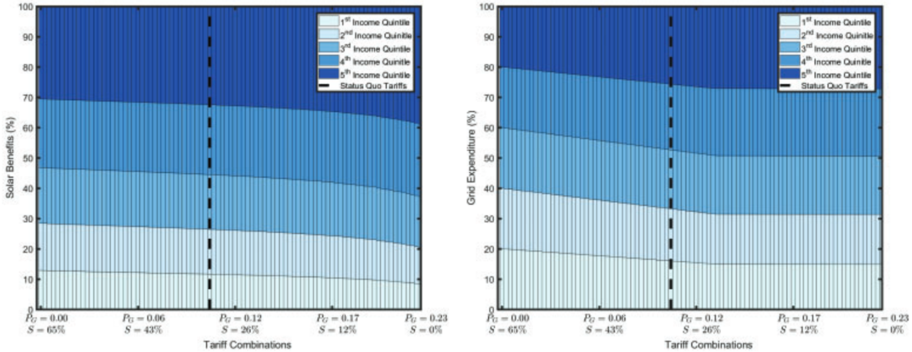

FIGURE 3

Distributional impacts of different tariff designs (7.5% solar energy target)

Conclusion

- Because of lower price elasticicty of rich households,marginal price increase is the most cost-efficient and progressive way to incentivize solar panel adoption, but high welfare loss.
- High fixed cost and high subsidy is the most expensive and regressive strategy, but achieves least welfare loss.
- Welfare/Equity objective gives an intermediate solution.
- Cost/Equity target has a slightly higher welfare loss, but lower costs and distribute grid expenditure more equally across households in different income quintiles.

References

Feger, F., Pavanini, N., & Radulescu, D. (2022). Welfare and redistribution in residential electricity markets with solar power. The Review of Economic Studies, 89(6), 3267-3302.