Residential Solar Panel Adoptions, Electricity Tariffs and Income Redistribution

Doina Radulescu

University of Bern, KPM, Oeschger Center for Climate Change Research and CESifo

January 22nd, 2020

AlpEnForCe, Energieforschungsgespräche Disentis
Outline

- Tariff Design and Welfare in Residential Solar Markets
- Income Redistribution vs. Environmental Concerns
Tariff Design and Welfare in Residential Solar Markets
Motivation - Reducing Emissions

- Governments worldwide aim at cutting fossil fuel emissions, keep global warming below $2^\circ C$ (now $1.5^\circ C$) (In 2015 195 countries have signed the Paris Agreement)

- Solar PhotoVoltaic (PV) is one of the main renewables
  - Between 2010-2019, USD 1,349 bn investments in solar capacities worldwide
Motivation - Development of Installed Capacity

- Global capacity increased from \( \sim 5 \) GW in 2005 to \( \sim 404 \) GW in 2017

- Solar PhotoVoltaic (PV) is one of the main renewables
  - Since 2017 contributes to more than 2% of global demand
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 inhabitant
  - 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, installation cost subsidy
   - Indirect: Two-parts tariff for electricity bill
     - Consumption-based tariffs (cent per kWh) to finance energy costs, network costs

2. Declining PV systems’ prices
   - From $\sim 7 \text{ USD/W in 2001}$ to $\sim 0.3 \text{ USD/W in 2017}$

Figure 11: Historical Market Incentives and Enablers

Source: IRENA PVPS
Wie die Zürcher Klimaallianz mit einem radikalen Vorstoß die Solarwende erzwingen will
13.06.2019

Bundesrat umgarnt Strombranche
Die Schweiz habe 30 Jahre, um klimaneutral zu werden. Diese Zeit reiche für grosse Veränderungen, wenn man nicht zögere, sondern jetzt entschlossen handle. Die Branche müsse die Stromproduktion aus einheimischen und erneuerbaren Quellen forcieren, damit die Dekarbonisierung vorankomme und die Versorgungssicherheit gewährleistet bleibe.[...] «Vehement investieren» müsse die Branche in die Photovoltaik, deren Chancen enorm seien.
17.01.2020
Motivation - Challenges from Growth in Solar PV

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 6 bn CHF additional grid costs from decentralized production until 2035.

- Paradox: The more efficient energy consumption becomes, the less households contribute to grid financing.

Who gets the bill?

California, net electricity-load requirement*

*Demand minus renewable generation

An increase of 10.9GW over three hours (February 1st 2016)

Source: California ISO
Motivation - Example

Direct Consumption: 1680 kWh
Battery: 1280 kWh
PV Energy Production: 8000 kWh
Energy Grid: 5040 kWh

37% Own Consumption: 2960 kWh
Missing Grid Revenue: 2960 kWh * 0.1 CHF/kWh = 296 CHF
Motivation - Challenges from Growth in Solar PV

**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
Motivation - Challenges from Growth in Solar PV

3 Cannibalization: Solar PVs produce at zero marginal costs, driving down energy prices

- Reduces incentive to adopt solar panels
Key Questions

- Are there undesirable income redistribution aspects in a system of PV installations and volumetric charges?
- How should optimal tariffs look like that
  - Guarantee network financing
  - Do not redistribute income
  - Incentivize PV adoptions
Contribution

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

- 2008-2014 yearly panel for 165k households in Bern (CH)
  - Data on electricity consumption, prices, income, wealth, demographics, PV adoption, building characteristics

- Estimate a dynamic structural model of households’ electricity consumption and PV adoption
## Literature

- **Electricity demand**: Reiss, White (2005), Ito (2014)
  
  ⇒ Exact match of household income & wealth data

  
  ⇒ First paper to combine energy consumption & PV adoption data, show how tariffs affect adoption

- **Network financing**: Borenstein (2008), Bushnell (2015)
Redistribution via one or two instruments

- Atkinson and Stiglitz (1976); Saez (2002); Kaplow (2006)
- Feldstein (1972a and b); Munk (1977); Cremer and Gahvari (2002)
- Sandmo (1975); Pirtilla and Tuomala (1997); Sjögren and Aronsson (2017)

Regressive/progressive effects of environmental levies and energy prices

- Hassett, Mathur and Metcalf (2009); Burtraw, Sweeney and Walls (2009); Chancel and Piketty (2015)
- Borenstein (2012); Levinson and Silva (2018)
The Dataset

Unique 2008-2014 yearly panel dataset for 165k 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
PV Investment Model

- Estimate energy price elasticities
- Household PV investment decision depends on
  - energy costs with/without a solar panel
  - investment costs
  - future remuneration of PV produced energy
- We can compute for each household the probability to install a PV
- Simulate how tariff changes influence the investment decision
⇒ Assign households to common border points (1km distance) and include border point fixed effects
Results Energy Demand

Elasticities across the income distribution

⇒ High income quintiles less elastic
Results PV Adoption

- 1 CHF reduction in installation costs weighs twice as much as 1 CHF increase in PV revenue.
Instruments of the Regulator

- **Volumetric charges** $P_G$: Stimulate investments in PV contribute to financing the network infrastructure, are progressive.

- **Subsidy of PV installations cost** $s$: Stimulates investment, requires additional financing.

- **Fixed fees** $f$: Contribute to network financing, no incentives to install a PV, are regressive.

⇒ Different solar energy and income redistribution targets require different combinations of tariffs.
Solar Energy Induced by Variable Price ($P_G$) and Subsidy ($s$)
Counterfactual Simulations

Death spiral:
- (a) 14.7% self-consumption
- (b) net metering (100% deduction of solar energy from electricity bill)
- Increase in grid tariff ($P_G$) to recover grid costs
- Change in energy bill across income quintiles
Future Adoption and Increase in Volumetric Charges (1)
Future Adoption and Increase in Volumetric Charges (2)
Change in $P_G, f, s$ to achieve 9% solar energy target, recover grid cost, minimize equity distortions. Account for grid integration costs of CHF 0.055/kWh

- Four different objective functions
  - Minimize grid expenditures ($Cost$)
  - Minimize grid costs and equitable grid cost distribution ($Cost/Equity$)
  - Maximize welfare ($Welfare$)
  - Maximize welfare and equitable grid cost distribution ($Welfare/Equity$)
<table>
<thead>
<tr>
<th>Instruments</th>
<th>% Price ($P_G$) Change</th>
<th>% Fixed Fee ($f$) Change</th>
<th>% Subsidy ($s$) as % $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost</td>
<td>Cost Equity</td>
<td>Welf</td>
</tr>
<tr>
<td></td>
<td>30.8</td>
<td>-1.9</td>
<td>-42.2</td>
</tr>
<tr>
<td></td>
<td>-95.3</td>
<td>22.3</td>
<td>173.5</td>
</tr>
<tr>
<td></td>
<td>62.0</td>
<td>72.5</td>
<td>86.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentage Change $GE_i$ by Inc. Quintile</th>
<th>1$^{st}$ Quintile</th>
<th>2$^{nd}$ Quintile</th>
<th>3$^{rd}$ Quintile</th>
<th>4$^{th}$ Quintile</th>
<th>5$^{th}$ Quintile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-12.1</td>
<td>9.9</td>
<td>38.3</td>
<td>15.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-8.5</td>
<td>9.4</td>
<td>32.5</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3.4</td>
<td>8.6</td>
<td>24.1</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>7.9</td>
<td>17.0</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>7.0</td>
<td>9.0</td>
<td>7.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentage Change $GE_i$ by PV</th>
<th>Non-PV HH</th>
<th>PV HH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.4</td>
<td>-16.2</td>
</tr>
<tr>
<td></td>
<td>7.4</td>
<td>-9.6</td>
</tr>
<tr>
<td></td>
<td>8.8</td>
<td>-1.2</td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>-8.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grid Integr. Cost (M CHF)</th>
<th>3.17</th>
<th>3.30</th>
<th>3.51</th>
<th>3.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidy Cost (CHF per kWh)</td>
<td>0.31</td>
<td>0.37</td>
<td>0.45</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Income Redistribution vs. Environmental Concerns
Affordability of Energy

Minister for the environment Altmaier: „Strom darf kein Luxusgut werden“ (2013)

Conservatives promise to cap prices in UK energy market (2017)

Theresa May promised to intervene in electricity markets if they “are thought to be failing ordinary families.” (The Guardian, 8.5.2017)
Energy Poverty vs. Environmental Concerns

Affordability of public utility services such as electricity is a salient issue in European and OECD countries.

- Expenditures on electricity represent 5% of annual annual income for the lowest income decile and 1% for the 10th decile in the Canton of Bern (Switzerland).
- In 2015, the poorest households in the EU spent on average 870€ on energy products (excl. transport) = 10% of total consumption expenditure.
- Poorest households spent only 3% of total expenditures on energy in Sweden, but up to 23% in Slovakia.

However

- The residential sector also contributes to around 17% of $CO_2$ emissions from fuel combustion with electricity and heat (IEA, 2018).
Protecting the Environment - Fighting Inequality
What We Do

- Analyse redistributinal effects of electricity prices in the presence of income taxation and environmental externalities.

- Controversies in the theoretical literature on the optimal direct-indirect tax mix (in economies with environmental externalities) call for more empirical work.
Findings

- **No externalities**: Redistribution concerns mostly require subsidisation of electricity prices in addition to progressive income tax.

- **Low inequality aversion and non zero externality costs**: Upward deviation from marginal cost. Pigouvian tax

- **Asymmetric information between regulator and utility**: Positive price mark-up.
Distribution of Electricity Consumption and Taxable Income
Optimal Markup for Different Degrees of Inequality Aversion and $\beta = -0.16$ or $\beta = -0.6$

Panel (I): $e = 0$

Panel (II): $e = 0.06$

Panel (III): $e = 0.12$
Conclusion

- 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.

- Our model can be applied to different types of networks infrastructures (i.e. highways, postal network) and be generalized to several household’s technology adoption decisions.

- The trade-off between equity and environmental concerns has implications for the design of electricity tariffs.
### Table: % Energy Prices, Network Tariffs and Taxes

<table>
<thead>
<tr>
<th></th>
<th>BKW Mean</th>
<th>BKW Std Dev</th>
<th>EWB Mean</th>
<th>EWB Std Dev</th>
<th>ET Mean</th>
<th>ET Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Fee Double Tariff (CHF/year)</td>
<td>153</td>
<td>27</td>
<td>121</td>
<td>22</td>
<td>111</td>
<td>19</td>
</tr>
<tr>
<td>Price High Tariff (Rp./kWh)</td>
<td>24.4</td>
<td>.8</td>
<td>19.7</td>
<td>1</td>
<td>25.6</td>
<td>.6</td>
</tr>
<tr>
<td>Energy Price</td>
<td>11.8</td>
<td>.3</td>
<td>11.6</td>
<td>.4</td>
<td>12.4</td>
<td>.2</td>
</tr>
<tr>
<td>Grid Price</td>
<td>10.4</td>
<td>1</td>
<td>7.3</td>
<td>.8</td>
<td>10.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Municipality Tax</td>
<td>1.8</td>
<td>.2</td>
<td>.4</td>
<td>.2</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>KEV Tariff</td>
<td>.4</td>
<td>.1</td>
<td>.4</td>
<td>.2</td>
<td>.5</td>
<td>0</td>
</tr>
<tr>
<td>Fixed Fee Uniform Tariff (CHF/year)</td>
<td>125</td>
<td>17</td>
<td>90</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price Uniform Tariff (Rp./kWh)</td>
<td>23.8</td>
<td>.6</td>
<td>18.2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Price</td>
<td>11.4</td>
<td>.4</td>
<td>10.5</td>
<td>.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid Price</td>
<td>10.2</td>
<td>1</td>
<td>6.8</td>
<td>.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipality Tax</td>
<td>1.8</td>
<td>.2</td>
<td>.5</td>
<td>.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KEV Tariff</td>
<td>.4</td>
<td>.1</td>
<td>.4</td>
<td>.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Table: % Energy Consumption and Expenditure

<table>
<thead>
<tr>
<th></th>
<th>N Obs</th>
<th>Mean</th>
<th>Std Dev</th>
<th>5th Perc</th>
<th>Median</th>
<th>95th Perc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumption (kWh)</td>
<td>872,715</td>
<td>4,139</td>
<td>3,805</td>
<td>812</td>
<td>3,022</td>
<td>11,045</td>
</tr>
<tr>
<td>Consumption High Tariff</td>
<td>538,232</td>
<td>2,439</td>
<td>1,940</td>
<td>544</td>
<td>1,977</td>
<td>5,978</td>
</tr>
<tr>
<td>Consumption Low Tariff</td>
<td>538,232</td>
<td>2,788</td>
<td>2,874</td>
<td>278</td>
<td>2,143</td>
<td>7,389</td>
</tr>
<tr>
<td>Consumption Uniform Tariff</td>
<td>334,483</td>
<td>2,303</td>
<td>1,622</td>
<td>662</td>
<td>1,919</td>
<td>5,161</td>
</tr>
<tr>
<td>Energy Expenditure (CHF)</td>
<td>872,715</td>
<td>928</td>
<td>702</td>
<td>267</td>
<td>738</td>
<td>2,226</td>
</tr>
<tr>
<td>Energy Price Expenditure (CHF)</td>
<td>872,715</td>
<td>409</td>
<td>350</td>
<td>88</td>
<td>313</td>
<td>1,053</td>
</tr>
<tr>
<td>Price Expenditure High Tariff</td>
<td>538,232</td>
<td>291</td>
<td>231</td>
<td>65</td>
<td>236</td>
<td>713</td>
</tr>
<tr>
<td>Price Expenditure Low Tariff</td>
<td>538,232</td>
<td>212</td>
<td>219</td>
<td>24</td>
<td>162</td>
<td>559</td>
</tr>
<tr>
<td>Price Expenditure Uniform Tariff</td>
<td>334,483</td>
<td>258</td>
<td>184</td>
<td>73</td>
<td>214</td>
<td>584</td>
</tr>
<tr>
<td>Grid Expenditure (CHF)</td>
<td>872,715</td>
<td>441</td>
<td>282</td>
<td>157</td>
<td>370</td>
<td>960</td>
</tr>
<tr>
<td>Tax Expenditure (CHF)</td>
<td>872,715</td>
<td>59</td>
<td>67</td>
<td>2</td>
<td>40</td>
<td>178</td>
</tr>
<tr>
<td>KEV Expenditure (CHF)</td>
<td>872,715</td>
<td>19</td>
<td>19</td>
<td>3</td>
<td>14</td>
<td>53</td>
</tr>
</tbody>
</table>
### % Income, Wealth and Tax Payments

<table>
<thead>
<tr>
<th></th>
<th>N Obs</th>
<th>Mean</th>
<th>Std Dev</th>
<th>5th Perc</th>
<th>Median</th>
<th>95th Perc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Income (CHF)</td>
<td>872,715</td>
<td>92,485</td>
<td>124,687</td>
<td>13,239</td>
<td>78,256</td>
<td>201,248</td>
</tr>
<tr>
<td>Taxable Income (CHF)</td>
<td>872,715</td>
<td>71,156</td>
<td>114,552</td>
<td>4,866</td>
<td>60,663</td>
<td>156,036</td>
</tr>
<tr>
<td>Total Wealth (CHF)</td>
<td>872,715</td>
<td>493,641</td>
<td>2029507</td>
<td>0</td>
<td>195,239</td>
<td>1571257</td>
</tr>
<tr>
<td>Cantonal Tax (CHF)</td>
<td>872,715</td>
<td>7,158</td>
<td>13,992</td>
<td>0</td>
<td>5,358</td>
<td>18,366</td>
</tr>
<tr>
<td>Municipal Tax (CHF)</td>
<td>872,715</td>
<td>3,682</td>
<td>6,840</td>
<td>0</td>
<td>2,807</td>
<td>9,350</td>
</tr>
<tr>
<td>Federal Tax (CHF)</td>
<td>872,715</td>
<td>1,654</td>
<td>9,141</td>
<td>0</td>
<td>454</td>
<td>5,845</td>
</tr>
</tbody>
</table>
### Table: % Simulated Capacity and Energy Production

<table>
<thead>
<tr>
<th></th>
<th>N Obs</th>
<th>Mean</th>
<th>Std Dev</th>
<th>5th Perc</th>
<th>Median</th>
<th>95th Perc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV Production Capacity (kWp)</strong></td>
<td>40,414</td>
<td>9.6</td>
<td>4.8</td>
<td>4.7</td>
<td>8.4</td>
<td>18.9</td>
</tr>
<tr>
<td><strong>PV Energy Production (kWh)</strong></td>
<td>40,414</td>
<td>9,697</td>
<td>5,604</td>
<td>4,708</td>
<td>8,354</td>
<td>19,133</td>
</tr>
<tr>
<td><strong>Self-Consumption</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of Production</td>
<td>40,414</td>
<td>14.7</td>
<td>9.6</td>
<td>5.1</td>
<td>12.3</td>
<td>33.4</td>
</tr>
<tr>
<td>% of Consumption</td>
<td>40,414</td>
<td>20.2</td>
<td>8.1</td>
<td>11.7</td>
<td>18.6</td>
<td>33</td>
</tr>
<tr>
<td>in kWh</td>
<td>40,414</td>
<td>1,213</td>
<td>861</td>
<td>592</td>
<td>982</td>
<td>2,616</td>
</tr>
</tbody>
</table>
Table: % PV Energy Production and Remuneration

<table>
<thead>
<tr>
<th>Variables</th>
<th>N Obs</th>
<th>Mean</th>
<th>Std Dev</th>
<th>5th Perc</th>
<th>Median</th>
<th>95th Perc</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Inverter Capacity (kVA)</td>
<td>4,401</td>
<td>8.1</td>
<td>8.6</td>
<td>2.2</td>
<td>6.2</td>
<td>20.7</td>
</tr>
<tr>
<td>PV Energy Production (kWh)</td>
<td>4,401</td>
<td>7,675</td>
<td>8,357</td>
<td>2,000</td>
<td>6,000</td>
<td>19,500</td>
</tr>
<tr>
<td>PV Remuneration (CHF)</td>
<td>4,401</td>
<td>3,368</td>
<td>2,189</td>
<td>1,338</td>
<td>2,722</td>
<td>7,667</td>
</tr>
<tr>
<td>Energy Consumption (kWh)</td>
<td>4,401</td>
<td>8,671</td>
<td>6,751</td>
<td>1,820</td>
<td>7,265</td>
<td>20,831</td>
</tr>
</tbody>
</table>
Figure: Distribution of PV installations by income
Richer Households More Likely to Adopt PV
Estimating the Model

Estimate household’s model in 3 steps

1. Static utility maximization to choose optimal electricity consumption, conditional on PV
   - Parameters of electricity demand with geographic RDD

2. Expectation over evolution of state variables that determine dynamic PV adoption decision
   - Parameters of transition probabilities

3. Dynamic utility maximization to adopt PV
   - Parameter of installation cost function and future revenues
Inequality and Redistribution

- Inequality is a key challenge for decades to come.

Trends in real household incomes at the bottom and the top, OECD average, 1985 = 1

Note: Income refers to disposable household income, corrected for household size. OECD is the unweighted average of 17 countries.


- Optimal policies to achieve redistribution still subject to considerable debate.
Individual Tax Burden Bern

![Graph showing Individual Tax Burden in Bern](image)

- Marginal Tax Rate
- Average Tax Rate

Income (CHF) vs. Marginal/Average Tax Rate