

Photovoltaics and the Solar Rebound: Evidence for Germany

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Renewables in Germany

- Federal support of Renewables through Renewable Energy Sources Act (EEG) and promotion via feed-in tariffs (FiT)
- More than 1 million rooftop solar installations of private households (ISE 2019)

⇒ Change in electricity consumption of PV households?

Rebound Effects

1 Classical Rebound Effect:

- Partial offset in savings following energy or fuel efficiency improvements as households increase use of appliance/car (Binswanger 2001; Frondel et al. 2008; Chan and Gillingham 2015)
- Explanation through income and price effects or moral licensing (Dütschke et al. 2018)

2 Solar Rebound Effect:

- Solar electricity is generated at zero marginal cost (Oliver et al. 2019) \Rightarrow Average price that solar households pay for electricity decreases \Rightarrow Increase in electricity consumption
- Empirical evidence for solar rebound for the US or Australia of about 15 to 21% (Havas et al. 2015; Deng and Newton 2017; Qiu et al. 2019)

Research Question and Policy Implication

Research Question: Do German solar households change their electricity consumption after installing a PV panel?

Evidence for a solar rebound in Germany implies:

- Total household electricity consumption increases
- Diminished potential of PV panels to reduce one-to-one the electricity taken from the grid

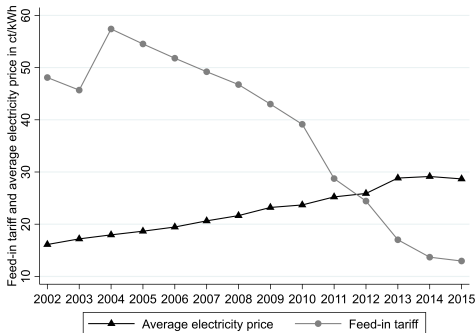
→ Reduced local environmental benefit

Background on PVs in Germany

- About 30% of solar generation is self-consumed (VZ 2020); rest is exported to the grid
- FiTs are guaranteed for up to 21 years and intertemporally fixed with level depending on the date of installation
- Solar FiTs were higher than the average electricity price between 2000 and 2012

Background on PVs in Germany

Figure: Average electricity prices for households with an annual electricity consumption of 3.500 kWh (BDEW 2016) and feed-in tariffs for solar households with a PV capacity below 10 kW (BNetzA 2020).



Data

Panel data set covering 12 years from 2004 - 2015

- Composed of 7 surveys from the *German Residential Energy Consumption Survey* (GRECS 2020)
- Socio-economic data, PV ownership, date of PV installation, grid electricity consumption eg, marginal electricity price p and total electricity costs of households
- 7,948 households that give information on PV ownership, grid electricity consumption and marginal electricity prices and costs
Installation
- 358 solar households (4.5%) → 4.8% in Germany 2015 Germany
- No data on solar electricity production epv and no data on total electricity consumption e

Summary

Data

Use of two instruments

- Instrument z_{PV} for likely endogenous PV variable: Number of PV systems within a zip code area (TSO 2017) → Peer effects (Bollinger and Gillingham 2012)
- Instrument z_p for likely endogenous price p : Sum of regulated price components as instrument (Frondel and Kussel 2019; Frondel et al. 2019)

Theoretical Framework

Electricity consumption of PV household:

$$e = eg(epv) + \theta \cdot epv, \quad (1)$$

where $eg = (1 - \theta)epv$ and $\theta =$ share of self-consumption.

Solar rebound SR :

$$\frac{\partial e}{\partial epv} = \frac{\partial eg}{\partial epv} + \theta \cdot \frac{\partial epv}{\partial epv} = \frac{\partial eg}{\partial epv} + \theta \quad (2)$$

If $\frac{\partial eg}{\partial epv} = 0$, SR is bounded from above by θ .

Theoretical Framework

As only the electricity taken from the grid eg is known, we can preclude the case of a maximum solar rebound by testing the following hypotheses:

$$H_0 : \frac{\partial \ln eg}{\partial PV} = 0 \quad \text{versus} \quad H_1 : \frac{\partial \ln eg}{\partial PV} < 0, \quad (3)$$

where PV is an indicator of a households's PV ownership.

Self-produced solar electricity first used to meet household's own demand
→ If eg remains unchanged, the household's total electricity consumption e increases, with the magnitude of the increase representing the solar rebound.

A Dynamic Panel Model

Effect of PV ownership on annual grid electricity consumption, eg , modeled as:

$$\ln(eg_{it}) = \beta_{t-1} \ln(eg_{i,t-1}) + \beta_{PV} PV_{it} + \beta_p \ln(p_{it}) + \beta_x^T \mathbf{x}_{it} + \tau_t + \mu_i + \nu_{it}$$

- $\ln(eg_{it})$ is the natural logarithm of the annual amount of electricity that household i takes in year t from the grid
- PV is an indicator of PV ownership
- $\ln(p)$ denotes the natural logarithm of the marginal electricity price
- \mathbf{x} is a vector comprising a set of socio-economic variables
- τ_t denotes year fixed effects that account for a general trend in the average household electricity consumption
- μ_i designates individual-specific fixed effects
- ν_{it} is an idiosyncratic error term

Dynamic Model Results

	Without Interaction Terms		With Interaction Terms	
	Coeff.	Std. Err.	Coeff.	Std. Err.
$\ln(\widehat{eg}_{t-1})$	0.626***	(0.074)	0.626***	(0.077)
$\widehat{\ln(p)}$	-0.326**	(0.145)	-0.278**	(0.130)
\widehat{PV}	-0.029	(0.053)	-0.037	(1.351)
$\widehat{PV} \times \widehat{\ln(p)}$	-	-	0.002	(0.451)
Socio-economic controls		Yes		Yes
Year Dummies		Yes		Yes
Number of observations		4,655		4,655
Number of instruments		50		57

Note: Standard errors clustered at the household level are in parentheses. ***, ** and * denote statistical significance at the 1 %, 5 % and 10 % level, respectively.

Robustness

Results

- Cannot reject $H_0 : \frac{\partial \ln eg}{\partial PV} = 0 \rightarrow$ Solar rebound bounded from above by share of self-consumption θ
- Solar rebound equal to 30% in Germany?
- FiTs above average electricity prices for majority of sample households:
 - Strong incentive to maximize feed-in and thus minimize household consumption during times of high solar generation (day)
 - Foregone remuneration of about € 680 per year for average solar household¹

→ Solar rebound likely to be much lower than 30%

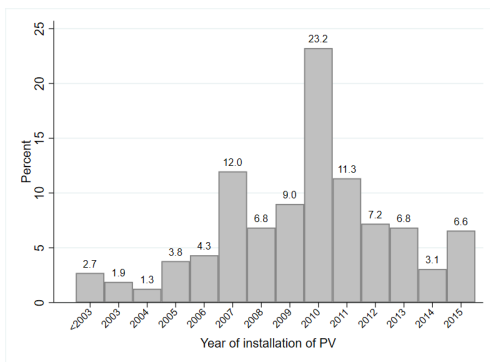
¹ Average installed capacity of 6.12 kW × full-load hours of 892 = 5,459 kWh. Average FiT of 41.5 cents/kWh.

Conclusions

- Indication that PV panel adoption in the survey period does not reduce amount of electricity that German households take from the public grid → Solar rebound
- Theoretical model suggests that rebound reaches a maximum, which is bounded by about 30% for German households
- No increased price awareness of solar households
- Sceptical that rebound is that high given strong incentive for German solar households to maximize their feed-in during survey period
- Slightly diminished local environmental benefit

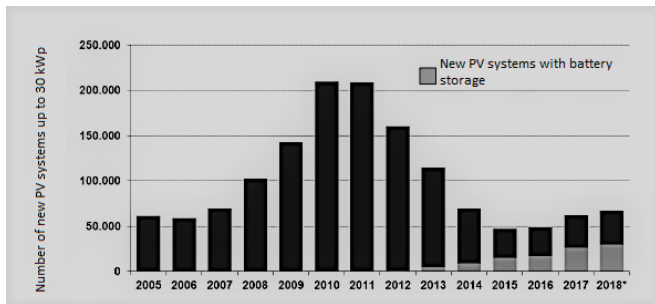
Annual Installations in the Sample

Figure: Year of PV Installation for Solar Households in the Estimation Sample. Source: German Residential Energy Consumption Survey (GRECS).



Annual Installations for Germany

Figure: Distribution of year of PV installation for households in Germany. Source: BSW-Solar 2019.



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Summary Statistics

Variable	All	No PV	PV	t-Statistic
Age	52.63	52.63	52.61	-0.05
Female	0.305	0.309	0.231	-4.42***
College	0.317	0.317	0.316	-0.08
Household size=1	0.186	0.191	0.078	-7.64***
Household size=2	0.432	0.434	0.393	-2.17**
Household size=3	0.171	0.168	0.232	4.43***
Household size=4	0.156	0.154	0.218	4.66***
Household size>4	0.054	0.053	0.079	3.01***
Homeowner	0.722	0.713	0.915	11.90***
Income	2,841	2,822	3,254	9.29***
<i>eg</i>	3,651	3,629	4,108	7.51***
<i>p</i>	21.06	21.03	21.78	4.22***
<i>ap</i>	24.40	24.38	24.68	1.42
<i>z_p</i>	12.20	12.20	12.18	-0.198
<i>z_{PV}</i>	131.35	127.17	218.89	14.20***

Note: ***, **, and * denote statistical significance at the 1%-, 5%-, and 10%-level, respectively.

Comparison with German Population

	2004			2015		
	Sample	Population	t-Statistic	Sample	Population	t-Statistic
Age < 25 years	2.8%	4.5%	-3.27***	0.0%	4.6%	-
Age 25-64 years	89.1%	67.5%	21.23***	56.7%	67.0%	-6.43***
Age > 64 years	8.2%	27.8%	-22.01***	42.7%	28.4%	8.94***
Female	27.9%	31.7%	-2.61***	35.4%	35.5%	-0.06
College	28.5%	11.0%	11.89***	29.0%	20.2%	5.94***
High income	11.4%	5.3%	5.65***	9.2%	11.4%	-2.26**
Household size = 1	10.1%	37.2%	-27.66***	30.0%	41.4%	-7.73***
Household size = 2	33.4%	34.1%	-0.45	52.8%	34.2%	11.52***
Household size = 3	20.9%	13.8%	5.35***	8.7%	12.1%	-3.69***
Household size = 4	25.5%	10.8%	10.32***	6.0%	9.0%	-3.86
Household size > 4	10.2%	4.1%	6.17***	2.5%	3.2%	-1.40
PV	1.1%	0.5%	1.56	4.2%	4.8%	-0.97

Note: Population data is drawn from the German TSOs (TSO 2017) and the German Federal Statistical Office (Destatis 2005; Destatis 2016). *** and ** denote statistical significance at the 1%- and 5%-level, respectively.

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Static Model Results

	Without Interaction Terms				With Interaction Terms	
	OLS		Fixed Effects		Fixed Effects	
	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
ln(p)	-0.108***	(0.020)	-0.038**	(0.016)	-0.036**	(0.017)
PV	0.021	(0.019)	-0.096***	(0.027)	0.016	(0.179)
PV × ln(p)	–	–	–	–	-0.036	(0.058)
ln(Income)	0.091***	(0.010)	0.020	(0.017)	0.020	(0.017)
Household size = 2	0.447***	(0.015)	0.290***	(0.032)	0.290***	(0.032)
Household size = 3	0.692***	(0.017)	0.438***	(0.036)	0.438***	(0.036)
Household size = 4	0.796***	(0.018)	0.515***	(0.036)	0.515***	(0.036)
Household size > 4	0.951***	(0.024)	0.595***	(0.043)	0.595***	(0.043)
College degree	-0.050***	(0.010)	0.017	(0.021)	0.018	(0.021)
Homeowner	0.164***	(0.011)	0.166***	(0.040)	0.166***	(0.040)
Age	0.006***	(0.000)	0.004	(0.003)	0.004	(0.003)
Female	-0.006	(0.010)	–	–	–	–
Year Dummies	Yes		Yes		Yes	
Number of observations	14,561		14,561		14,561	

Note: Standard errors clustered at the household level are in parentheses. ***, ** and * denote statistical significance at the 1 %, 5 % and 10 % level, respectively.

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First Stage Results

	Standard 2SLS		Fixed Effects 2SLS	
	Price	PV	Price	PV
	Coeff.	Coeff.	Coeff.	Coeff.
z_{PV}	-0.000	0.0001***	-0.000	0.0001**
z_p	0.279***	-0.088**	0.202***	0.093*
ln(Income)	-0.002	0.011**	0.012	-0.008
Household size = 2	-0.022***	0.007	-0.042**	0.003
Household size = 3	-0.022***	0.025**	-0.052***	-0.003
Household size = 4	-0.023***	0.016	-0.035	-0.001
Household size > 4	-0.021**	0.029*	-0.027	0.019
College	0.008**	-0.001	0.021	-0.038*
Homeowner	-0.006	0.033***	-0.034	0.000
Age	-0.001***	-0.000	0.001	0.000**
Female	-0.003	-0.013**	-	-
Year Dummies	Yes	Yes	Yes	Yes
Number of observations	12,524	12,524	12,524	12,524
Kleibergen-Paap F statistic		16.81		6.12

Note: Standard errors clustered at the household level are in parentheses. ***, ** and * denote statistical significance at the 1 %, 5 % and 10 % level, respectively.

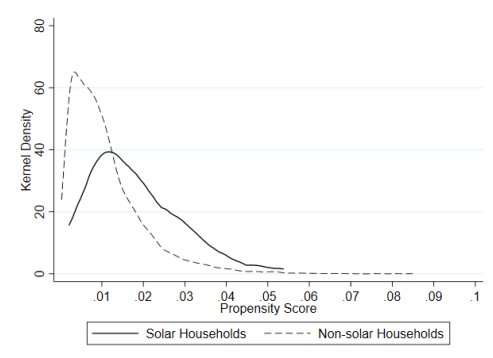
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Matching Results

	Without Interaction Terms		With Interaction Terms	
	Coeff.	Std. Err.	Coeff.	Std. Err.
$\ln(eg_{t-1})$	0.614***	(0.084)	0.607***	(0.080)
$\widehat{\ln(p)}$	-0.315*	(0.185)	-0.251	(0.182)
\widehat{PV}	-0.088	(0.059)	-1.077	(1.768)
$\widehat{PV} \times \widehat{\ln(p)}$	-	-	0.343	(0.602)
Socio-economic controls		Yes		Yes
Year Dummies		Yes		Yes
Number of observations		4,488		4,488
Number of instruments		50		55

Note: Standard errors clustered at the household level are in parentheses. ***, ** and * denote statistical significance at the 1 %, 5 % and 10 % level, respectively.

Figure: Check for Common Support Assumption for Propensity Score Matching Results.



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Results with average price

	Without Interaction Terms		With Interaction Terms	
	Coeff.	Std. Err.	Coeff.	Std. Err.
$\ln(eg_{t-1})$	0.622***	(0.069)	0.613***	(0.066)
$\widehat{\ln(ap)}$	-0.433***	(0.163)	-0.332**	(0.161)
\widehat{PV}	-0.002	(0.042)	2.196	(2.375)
$\widehat{PV} \times \widehat{\ln(ap)}$	-	-	-0.688	(0.741)
Socio-economic controls		Yes		Yes
Year Dummies		Yes		Yes
Number of observations		4,655		4,655
Number of instruments		50		57

Note: Standard errors clustered at the household level are in parentheses. ***, ** and * denote statistical significance at the 1 %, 5 % and 10 % level, respectively.

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