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 2021)

$\Rightarrow$ 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

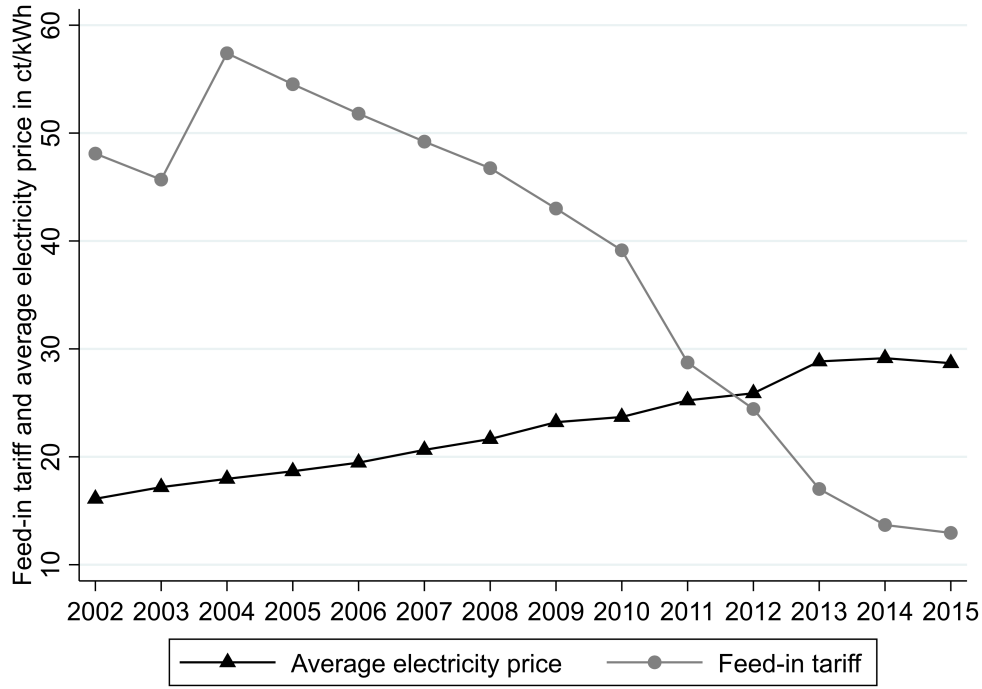
$\rightarrow$ Reduced local environmental benefit

Background on PVs in Germany

- About 25% of solar generation is self-consumed (ZSW, Bosch & Partner 2019); 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
- System of net feed-in: Solar rebound may be driven by price and income effect

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
- About 50% reported relevant information at least twice
- 7,948 households that give relevant information Installation
- 358 solar households (4.5%) $\rightarrow$ 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) $\rightarrow$ 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:

$$e = eg(epv) + \theta \cdot epv, \tag{1}$$

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

Solar rebound SR:

$$\frac{\partial e}{\partial epv} = \frac{\partial eg}{\partial epv} + \theta \cdot \frac{\partial epv}{\partial epv} = \frac{\partial eg}{\partial epv} + \theta \tag{2}$$

If no change in grid consumption, $\frac{\partial eg}{\partial epv} = 0 \rightarrow \frac{\partial e}{\partial epv} = \theta$.

$$SR = \frac{\partial \ln e}{\partial \ln epv} = \frac{epv}{e}\frac{\partial e}{\partial epv} = \frac{epv}{e}\theta < 2\theta \tag{3}$$

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:

$$H_0 : \frac{\Delta \ln eg}{\Delta PV} = 0 \qquad \text{versus} \qquad H_1 : \frac{\Delta \ln eg}{\Delta PV} < 0, \tag{4}$$

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

Self-produced solar electricity first used to meet household's own demand
$\rightarrow$ If *eg* remains unchanged, the household's total electricity consumption *e* increases

A Dynamic Panel Model

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

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

- $\ln(eg_{it})$ 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
- $\boldsymbol{x}$ 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 invidual-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.
$\ln(eg_{t-1})$	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 $H_0 : \frac{\Delta \ln eg}{\Delta PV} = 0 \rightarrow$ Solar rebound bounded by 2θ
- Solar rebound (SR) equal to 50% in Germany?
  - Estimate of SR if decrease in grid consumption by 2.9%:
    - $1 - [(0.25 \times 5,500 + (1 - 0.029)3,650)/3,650] = 35\%$[1]
  - Estimate of SR if no change in grid consumption:
    - $1 - [(0.25 \times 5,500 + 3,650)/3,650] = 38\%$

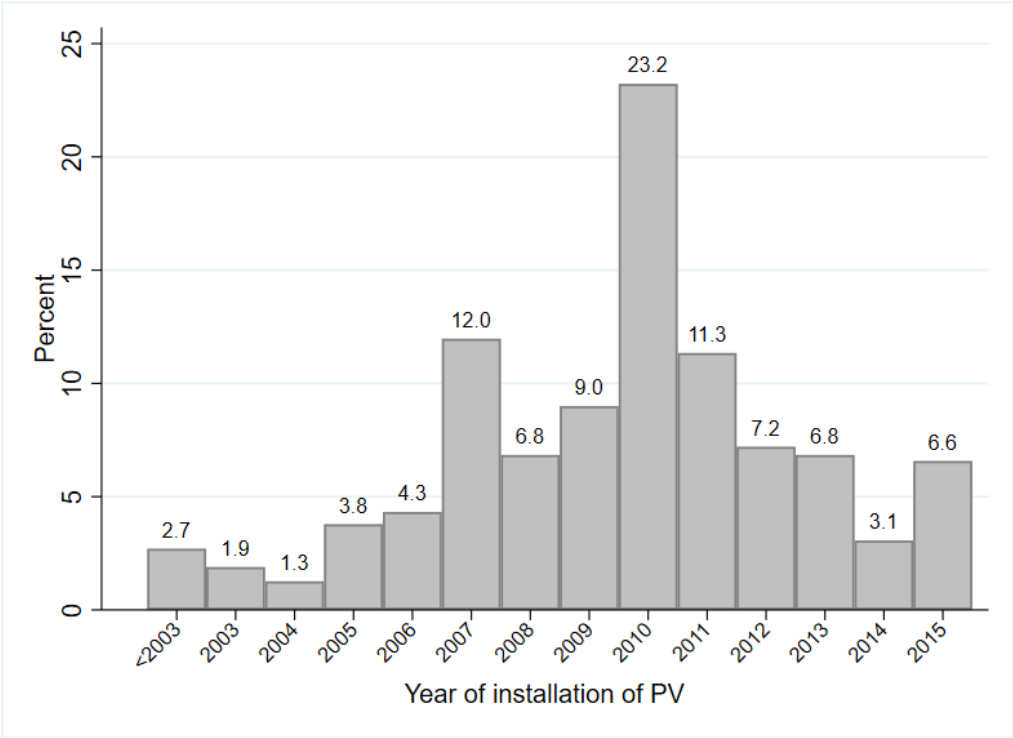
[1] Taking the mean annual household electricity consumption of 3,650 kWh and a mean PV production of 5,500 kWh, the solar rebound can be gauged at $1 - [(0.25 \times 5,500 + (1 - 0.029)3,650)/3,650] = 35\%$, given that $0.25 \times 5,500 + (1 - 0.029)3,650$ reflects the total electricity consumption in the aftermath of PV adoption.

Conclusions

- Panel data allowed estimation of a dynamic model that accounts for sluggish appliance stock adjustments and for unobserved heterogeneity
- Indication of a solar rebound, bounded by 50% for German households
  - Sceptical that rebound is that high given high feed-in tariffs
  - Back-of-the-envelope calculation suggests rebound of around 35%
- Slightly diminished local environmental benefit
- Moderate rebound expected in future despite falling feed-in tariffs

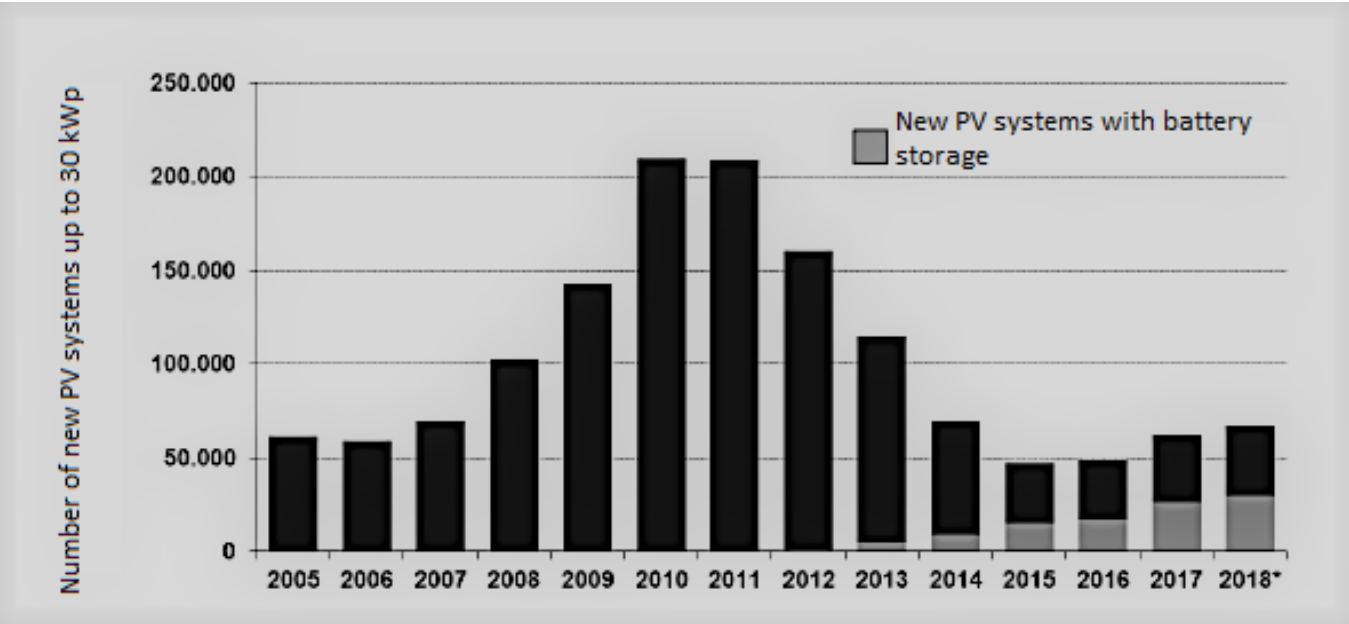
Annual Installations in the Sample

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***
eg	3,651	3,629	4,108	7.51***
p	21.06	21.03	21.78	4.22***
ap	24.40	24.38	24.68	1.42
z_p	12.20	12.20	12.18	-0.198
z_{PV}	131.35	127.17	218.89	14.20***

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

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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$\times$ 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**
ln 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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Placebo Test for Validity of PV Instrument

	Fixed Effects	
	Coeff.	Std. Err.
ln(p)	-0.035**	(0.017)
z_{PV}	-0.000	(0.000)
ln(Income)	0.018	(0.018)
Household size = 2	0.282***	(0.032)
Household size = 3	0.441***	(0.036)
Household size = 4	0.517***	(0.036)
Household size > 4	0.595***	(0.044)
College degree	0.021	(0.023)
Homeowner	0.173***	(0.043)
Age	0.004	(0.003)
Constant	7.477***	(0.218)
Year Dummies	Yes	
Number of observations	13,855	

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

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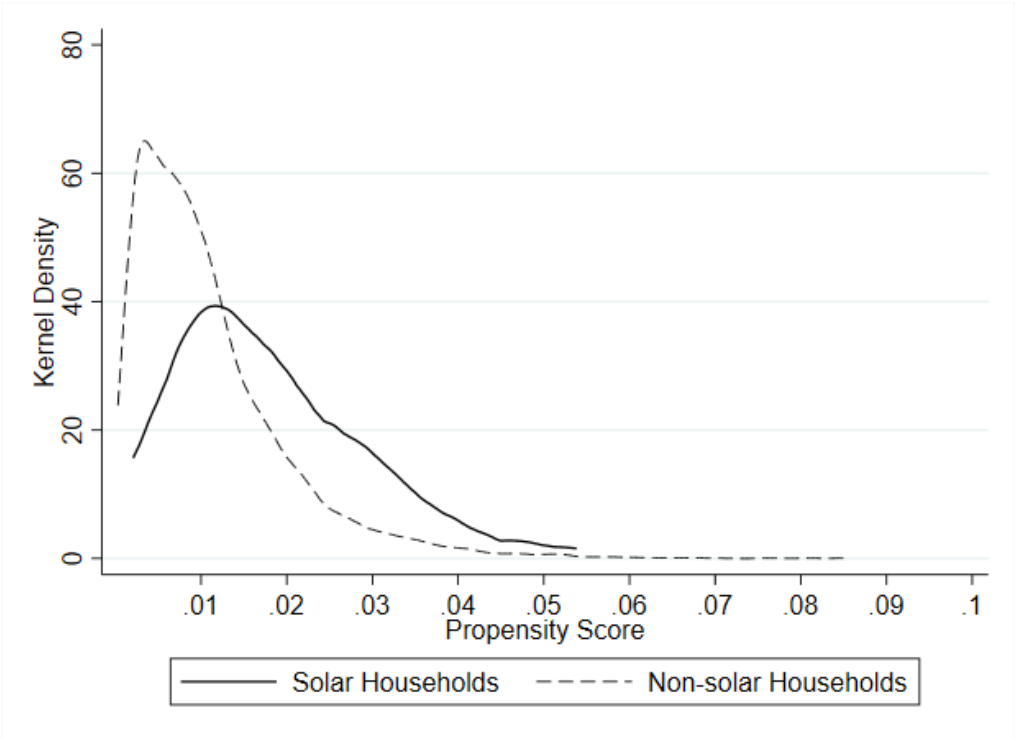
Matching Results

	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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