Q-complementarity in household adoption of photovoltaics and electricity-intensive goods: The case of electric vehicles

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Integration of Loads and Electric Storage Systems into Advanced Flexibility Schemes for LV Networks

Adoption research

- There is much interest in solar (PV) and electric vehicle (EV) adoption
- Prosumerism and citizen participation in the energy transition are EU goals (e.g. SET Plan)
- Many research papers look into the determinants of household adoption decisions

Past solar adoption research has shown:

- Return on investment (ROI) and incentive policies matter (Crago and Chernyakhovskiy, 2017 *JEEM*).
- Choice of adoption and scale of adoption are systematically different (Beckman and Xiarchos, 2013 *Renewable Energy*).
- Personal environmental motivations and life-cycle considerations are also important (Schelly, 2014 *ERSS*).

Past EV adoption research has shown:

- High initial cost is a major hurdle to adoption (Rezvani et al., 2015 *Transportation Research Part D*).
- Lack of charging infrastructure is a big barrier (Biresselioglu et al., 2018 *Transportation Research Part A*).
- Lack of trust in new technology and 'range anxiety' are also barriers (Biresselioglu et al., 2018 *Transportation Research Part A*).

No past research has investigated the link between household PV, and large appliance adoption

- Large appliances imply higher energy consumption, and more room to offset household energy costs
- Some large appliances can be loadshifted, to use more household-produced solar
  - this can save more money and increase ROI,
  - and increase perception of environmental action/ self-sufficiency
- With this knowledge we can better understand energy behavior and the indirect effects of policies and social innovations

Q-complements: linking PV adoption to large appliance ownership

The goods Y_1 (PV) and Y_2 (EV) are q-complements if for some utility function $U(Y_1, Y_2, Z)$:

$$\frac{\partial^2 U}{\partial Y_1 \partial Y_2} > 0$$

We show theoretically that this condition implies correlated demands for PV units and EVs.

People consume these goods in small, discrete quantities.

In a random utility framework with a linear representation we have:

$$U_i(Y_{1i}, Y_{2i}, Z_i | M_i, p_1, p_2) = \gamma_i Z_i + \alpha_{1i} Y_{1i} + \alpha_{2i} Y_{2i} + \alpha_{3i} Y_{1i} Y_{2i} + \hat{\epsilon}_i$$

Where $\alpha_{3i} > 0 \implies$ q-complementarity between the goods

Imagine a situation where the household i has already purchased a PV unit ($Y_{1i} = 1$), and considers getting an EV:

$$U_i(1, Z_i | Y_{1i} = 1, M_i - p_1, p_2) - U_i(0, Z_i | Y_{1i} = 1, M_i - p_1, p_2)$$
$$= \alpha_{2i} + \alpha_{3i} - \gamma_i p_2 + (\dot{\epsilon}_i - \acute{\epsilon}_i)$$

Adoption occurs if: $U_i(1, \cdot) - U_i(0, \cdot) > 0$

And when

$\alpha_{3i} > 0 \implies E[U_i(1, \cdot) - U_i(0, \cdot)]$ is higher.

Over a sample of households, this implies we should observe correlated demands for q-complimentary goods

Research Objectives

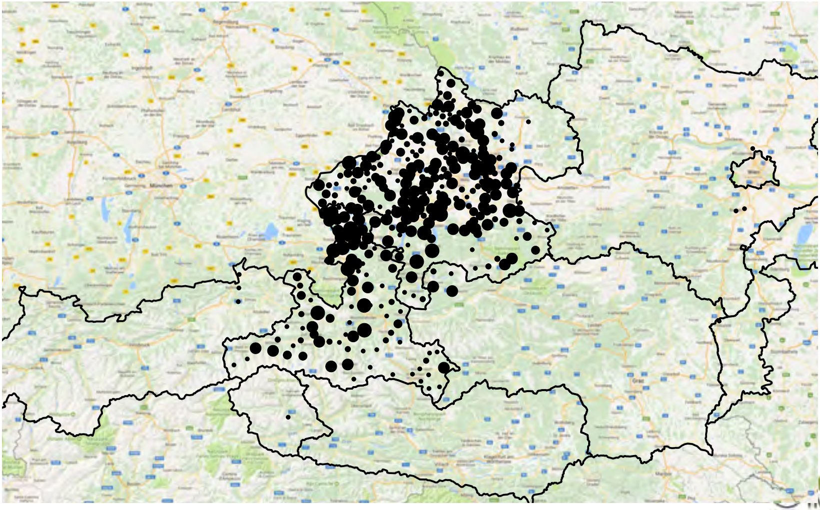
- Better understand the interrelation between important household appliance purchases
- Draw inference about α_3 through statistical models
  - If $\alpha_3 > 0$ then we have q-complementarity between PV adoption and large ticket purchases, notably EV
- Identify potential unintended consequences or benefits from solar, EV, or energy efficiency policy

Data on PV and appliance ownership

LEAFS project survey:

- Collected data from household electricity customers in Summer, 2018
- Covered two Austrian states: Upper Austria and Salzburg
- Asked about the ownership of household appliances, and plans to change energy practices
- Socio-demographic information and past actions/views were also collected

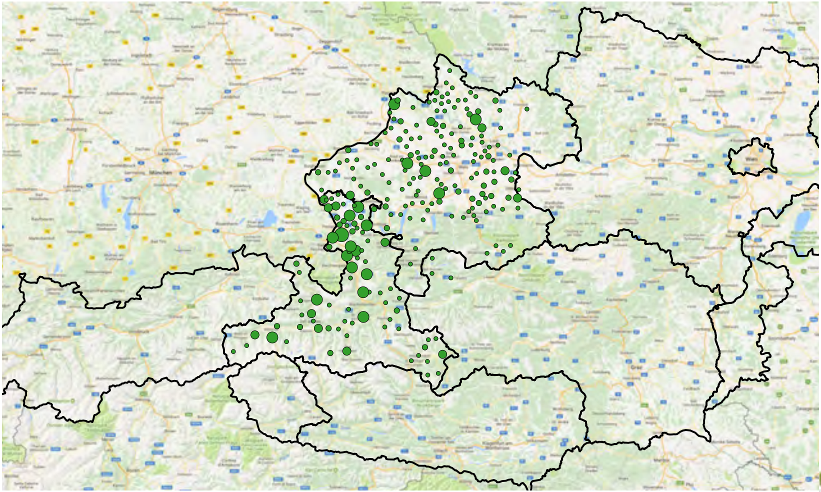
Survey respondents aggregated by postal code region



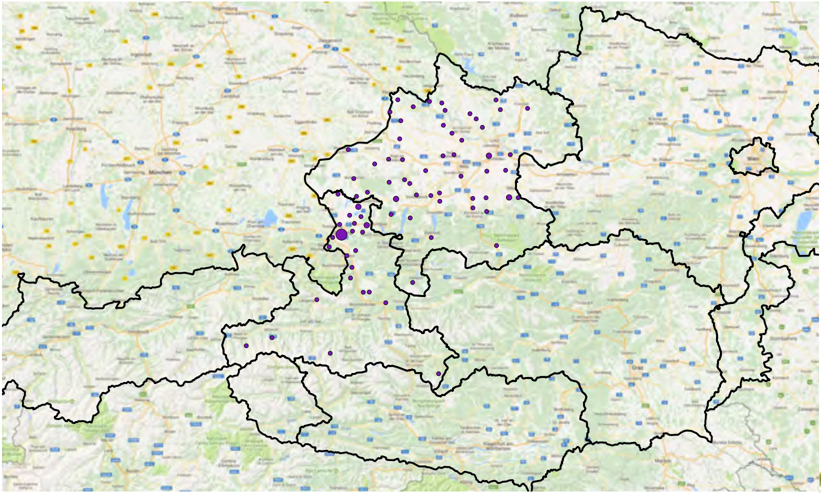
PV and EV adoption in survey respondents

	PV ownership		
EV ownership	**not owned**	**owned**	**Total**
not owned	1 865	569	2 434
owned	32	75	107
Total	1 897	644	2 541

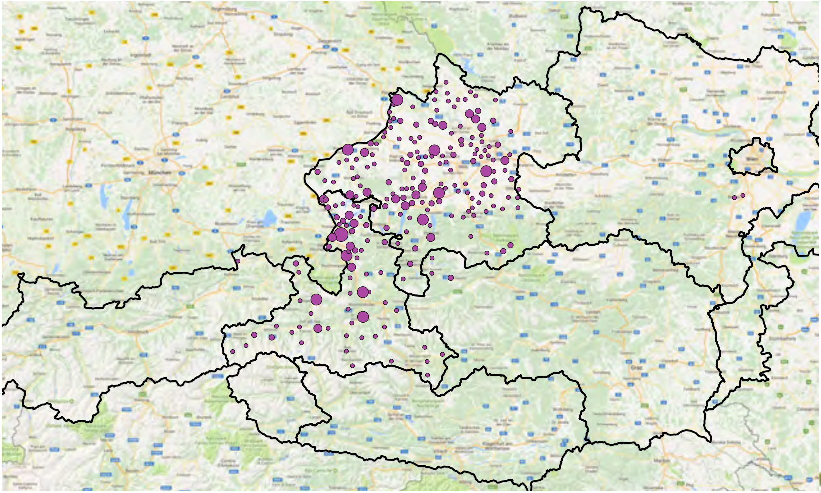
Locations of PV owners



Locations of EV owners



Locations of future EV purchasers



Explanatory variables from the survey

Variable	Description	Mean	Median	Std. Dev.
PV_ownership	=1 if HH owns a PV system	0.25	0	0.44
EV_ownership	=1 if HH owns an EV	0.04	0	0.20
*EV_plan**	=1 if HH plans to buy an EV in next 5 years	0.25	0	0.43
electric_heat	=1 if the HH's main heater uses electricity	0.23	0	0.42
dryer_ownership	=1 if HH owns an electric dryer	0.61	1	0.49
pool_ownership	=1 if HH owns a swimming pool	0.19	0	0.39
aquarium_ownership	=1 if HH owns an aquarium	0.04	0	0.20
waterbed_ownership	=1 if HH owns a waterbed	0.04	0	0.19
sauna_ownership	=1 if HH owns a sauna	0.33	0	0.47
owns_home	=1 if HH owns their residence	0.88	1	0.33
livingspace_home	sq. meters of indoor living space	155.30	140	76.19
singlefamily_home	=1 if the HH lives in a detached home or duplex	0.76	1	0.43
household_size	Number of persons in HH	2.74	2	1.26
income_cat1	=1 if monthly HH net income $< 1,800$ EUR	0.16	0	0.36
income_cat2	=1 if monthly HH net income 1,800-2,900 EUR	0.36	0	0.48
income_cat3	=1 if monthly HH net income 2,900-4,400 EUR	0.34	0	0.47
income_cat4	=1 if monthly HH net income $> 4,400$ EUR	0.15	0	0.35
high_environmentalism	=1 if HH believes environment/climate are "primarily" or "very" important in enery issues	0.79	1	0.41
UpperAT	=1 if resident is from the state of Upper Austria	0.68	1	0.47
population	population in postal code region 1000's of persons	18.17	3.33	66.13
leftvoters	Pct. of postal code region that voted for "SPOE" political party in last election	26.16	22.99	6.97

N= 2,541; HH = household; *N=2,434 for this variable as the 107 HHs who already own EV are dropped.

Correlations in appliance purchases

	pv_own	*ecar_own*	*heat_gridtied*	*dryer*	*pool*	*aqua*	*waterbed*	*sauna*
pv_own	1							
ecar_own	0,2255	1						
heat_gridtied	0,1537	0,0266	1					
dryer	0,1261	0,0254	0,0868	1				
pool	0,0808	0,053	0,0507	0,1765	1			
aqua	0,0372	-0,0151	0,0065	0,0748	0,0598	1		
waterbed	0,0301	0,0158	0,0121	0,0768	0,132	0,0712	1	
sauna	0,1133	0,0591	0,0539	0,1389	0,241	0,0135	0,0715	1

Probit model

We use probit specifications to model binary adoption choice

$$
\begin{aligned}
& y_i = 1 \quad \text{if} \quad y_i^* > 0 \\
& y_i = 0 \quad \text{otherwise} \\
& \text{with} \\
& y_i^* = \boldsymbol{\beta}' \mathbf{x}_i + \epsilon_i, \quad \epsilon \sim N(0,1)
\end{aligned}
$$

where y_i^* is a latent variable measuring the change in utility from adopting an appliance

Probit model results predicting PV and EV ownership

	Dependent Variable is *PV_ownership*		Dependent Variable is *EV_ownership*	
	Marg. Eff.	**Std. Err.**	**Marg. Eff.**	**Std. Err.**
EV_ownership	0.314***	(0.0329)		
PV_ownership			0.0770***	(0.00943)
electric_heat	0.0961***	(0.0167)	-0.0104	(0.00935)
dryer_ownership	0.0279*	(0.0169)	-0.0059	(0.00835)
pool_ownership	0.0372*	(0.0200)	0.00453	(0.00933)
aquarium_ownership	0.0189	(0.0351)	-0.0284	(0.0217)
waterbed_ownership	0.0180	(0.0386)	0.0183	(0.0185)
sauna_ownership	0.0417**	(0.0169)	0.00746	(0.00814)
owns_home	0.0800**	(0.0342)	0.00117	(0.0163)
livingspace_home	0.000537***	(0.000117)	0.0000251	(0.0000504)
singlefamily_home	0.107***	(0.0242)	-0.00657	(0.0112)
household_size	0.0346***	(0.00675)	-0.000188	(0.00318)
income_cat1 (<1800)	-	-	-	-
income_cat2 (1800-2900)	0.0213	(0.0251)	0.00757	(0.00914)
income_cat3 (2900-4400)	-0.00764	(0.0248)	0.0292***	(0.0106)
income_cat4 (>4400)	-0.00760	(0.0293)	0.0329**	(0.0137)
high_environmentalism	0.0376**	(0.0186)	0.0194*	(0.0108)
UpperAT	-0.248***	(0.0176)	0.00901	(0.00917)
population (1000's)	-0.000673**	(0.000247)	0.0000828	(0.000109)
leftvoters (%)	-0.00503***	(0.00116)	0.000257	(0.000620)
Pseudo R-sq.		0.2		0.14

N= 2,541 ; * p<0.1, ** p<0.05, *** p<0.01

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Endogeneity between PV and EV adoption

If decision to adopt is made jointly, as suggested by our theory, or similar unobservables influence both decisions (e.g. localized incentives, peer effects, etc.)

Test this with Recursive Bivariate Probit:

$$y^*_{1i} = \beta' \mathbf{x}_{1i} + \alpha y_{2i} + \epsilon_{1i}$$
$$y^*_{2i} = \beta' \mathbf{x}_{2i} + \epsilon_{2i}$$

with

$$\left[\epsilon_{1i}, \epsilon_{2i}\right] \sim \Phi\left[(0,0),(1,1),\zeta\right], \quad \zeta \in \left[-1,1\right]$$

Where ζ is an estimable correlation parameter. We test the hypothesis $\zeta = 0$ and cannot reject at the 1% level, implying endogeneity exists

Table: Partial effects from recursive bivariate probit model on future planned EV purchase with PV ownership endogenously determined

Variable	Sample excluding current EV owners N = 2,434 Marg. Eff	Std. Err.	Z-stat.	Prob>Z
PV_ownership	0.1867*	0.1071	1.74	0.08
owns_home	0.045	0.0324	1.40	0.162
livingspace_home	0.0002	0.0002	1.13	0.258
singlefamily_home	-0.0255	0.0277	-0.92	0.356
household_size	0.0020	0.009	0.22	0.823
income_cat1 (<1800)				
income_cat2 (1800-2900)	0.0763***	0.0245	3.12	0.002
income_cat3 (2900-4400)	0.093***	0.0251	3.71	0.000
income_cat4 (>4400)	0.1651***	0.0327	5.05	0.000
high_environmentalism	0.0636***	0.0226	2.83	0.005
UpperAT	-0.0186	0.042	-0.44	0.657
population (1000's)	0.0005*	0.0003	1.86	0.062
leftvoters (%)	-0.0002	0.0014	-0.14	0.889

* p<0.1, ** p<0.05, *** p<0.01

Conclusions

1. There exists evidence for q-complementarity between PV and electricity-intensive appliances
    - Most strongly EVs
    - Also for electric central heaters, dryers, saunas, and pools
2. This would mean that policies which increase PV adoption may have the added benefit of increasing EV adoption.
3. Conversely, policies that increase energy efficiency, or reduce quantities of large appliances may reduce PV adoptions.
4. Recognizing unintended consequences is important with so many policies focused on EV, PV, and energy efficiency.

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