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

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ABSTRACT

Photovoltaic (PV) units and electric vehicles (EVs) are two household goods that are the focus of much research, and many policy initiatives attempting to promote a more sustainable, low-carbon energy system. Despite both academic and practical interest in household adoption of PV units and EVs, potential linkages in these household decisions have only just begun to be explored. This paper presents q-complementarity between the goods as one possible form of a linkage between PV and EV purchases that is based on economic utility theory. We posit the goods could be q-complements due to a PV-owning household's ability to offset and shift their electricity load from EV charging to increase the self-consumption of 'home-made' electricity, thereby increasing the positive feelings of environmental efficacy and monetary returns from the PV unit. We use data from 2541 internet surveys of Austrian residential electricity customers collected in 2018 to explore these hypotheses. Probit models of household EV and PV adoption choice are estimated, including a recursive bivariate probit model of households who plan to purchase an EV in the future, with PV ownership endogenously determined. Controlling for household income, characteristics, environmental attitudes, and neighborhood characteristics, we find that EV and PV adoption are positively correlated, and that current PV unit owners are 21% more likely to plan an EV purchase in the next 5 years compared to non-PV owners. We interpret these results as evidence in support of our hypothesis of q-complementarity between PV units and EVs, and note the potential for added benefits from incentive policies promoting adoption of one good or the other that this linkage suggests.

1. Introduction

Many past studies have investigated the driving factors and attitudes behind household adoption of low-carbon, pro-environmental energy items, especially PV (photovoltaic) units and EV (electric vehicles). From the regulatory perspective, The European Commission's Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles and the revised Renewable Energy Directive 2018/2001/EU both support a broad market uptake of environmentally-friendly vehicles and set new renewable energy targets of a 32% renewable consumption share for the EU by 2030. In this regard, several studies focus on the potential of EVs to facilitate the integration of renewable energy into the power system (Longo et al., 2018; Parsons et al., 2014; Kempton and Letendre, 1997). The capability of EVs to charge and discharge energy during specific times (charge during high renewable energy production periods and discharge during times of peak demand) might enable a faster, and cheaper, uptake of intermittent renewable energy sources into the grid, while also increasing the overall stability of the grid. From the consumer's perspective, both technologies show increasing adoption rates, as shown in Fig. 1 for our case study market of Austria, and have not yet reached full market saturation — leaving ample potential for further integration and market development.

In terms of the household adoption decision, return-on-investment (ROI) and other financial factors have been shown to be important drivers of a household's choice to adopt PV (Crago and Chernyakhovskiy, 2017; Krasko and Doris, 2013; Haas et al., 1999).

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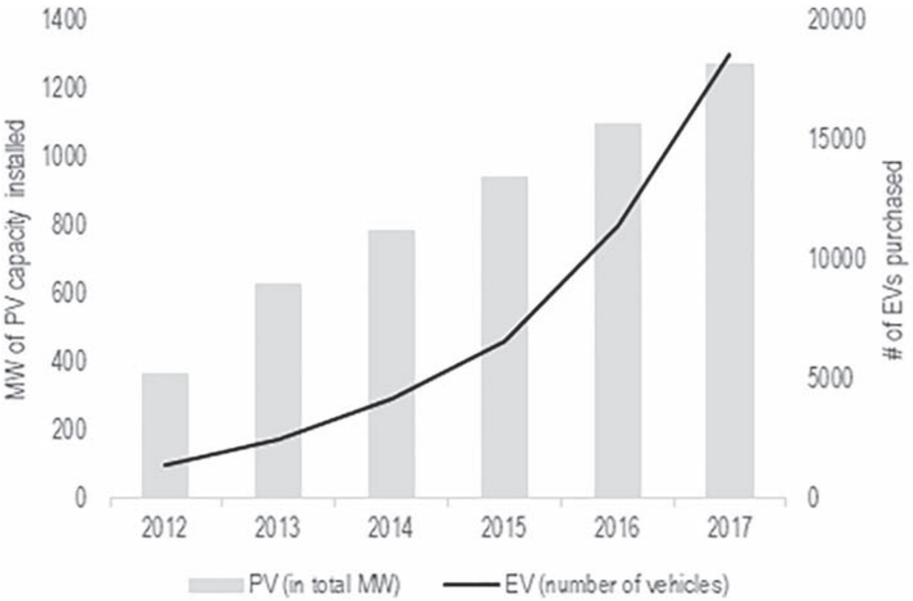

Fig. 1. Cumulative deployment of PV and EVs in Austria since 2012.

Not surprisingly, households also consider financial factors when deciding to purchase an EV (Sierzchula et al., 2014a). Feasibility of installation due to building type, geographic constraints, and household income are also important determinants of PV adoption (Wang et al., 2017). Similarly, high initial costs and income barriers have been shown to deter EV adoption (Rezvani et al., 2015). Furthermore, individual and communal environmentalist attitudes, as well as comfort levels with new technologies, have been shown to drive EV and PV adoption (Noll et al., 2014; Rezvani et al., 2015; Haas et al., 1999; Egbue and Long, 2012; Schuitema et al., 2013). Specific to the context of EV adoption, the literature also mentions personal comfort related to range considerations and the availability of public charging infrastructure as factors in the adoption decision (Coffman et al., 2017; Sierzchula et al., 2014b). Schelly (2014) shows, through in-depth interviews with PV adopters in the U.S., that attitudes and financial concerns are important, but that life-cycle concerns can influence the *timing* of PV adoption, such that idiosyncrasies (stochasticity) in a cross-sectional view of household adoption at a single point in time should be expected.

This paper takes a step past the study of factors driving adoption of PV and EV, to look into the potential relationship between these two decisions, using data from a survey completed in Austria. Specifically, we posit that PV and EV technologies may be q-complements in household utility, as defined in Eq. (1), such that the welfare gain (benefits) from adopting one of these technologies is increased if the other technology is also owned/adopted. This condition could also hold between other electricity-intensive appliances and PV. The intuition behind this supposition is due to the fact that the joint ownership of electricity-intensive appliances and a PV unit can allow for greater loadshifting potential, where the household shifts the times of electricity use to deploy more ‘home-made’ solar power in the home. Thus, owning a PV system in tandem with other electricity-intensive items and/or EV, could improve the utility gained from these items through the following two avenues:

1. Increasing the households’ perception of their environmental efficacy, and their interest in energy topics.
2. Saving money and increasing ROI from the investment in a PV unit.

As to point 1 above, directly consuming renewable power from domestic PV generation may allow for feelings of sufficiency and pro-environmentalism within families and increase the benefits from the PV installation. Indeed, empirical research has shown that consumers in Germany are willing to pay more for electricity produced by renewable sources, suggesting a preference for ‘green’ electrons (Sagebiel et al., 2014; Rommel et al., 2016). Furthermore, a stated preference, elicited via choice experiments, for electricity that is locally-produced, or sourced from distributed suppliers has been shown in several studies in Germany (Sagebiel et al., 2014; Kalkbrenner et al., 2017; Rommel and Sagebiel, 2017). With these results in hand, it is only a small intuitive leap to suggest that some consumers may have a preference for power that they produce themselves. In addition, psychologists have argued that adopting PV can make energy issues more interesting and rewarding for households through greater information and engagement with the effects of their energy choices (Ryghaug et al., 2018). This may then improve utility gains from future ‘green’ appliance purchases such as EVs.

These lines of reasoning are upheld by the findings of Wittenberg and Matthies (2018) in their study of how German PV owners use their PV systems and change their electricity use. Specifically, the authors use a survey of 367 German citizens to find that PV owners embrace ‘sufficiency’ attitudes, and engage in loadshifting activities, with the majority of households reporting that they carry-out manual loadshifting activities “most of the time” (Wittenberg and Matthies, 2018). Similar results were found for PV adopters from the UK, Japan, and Austria (Haas et al., 1999; Hondo and Baba, 2010; Keirstead, 2007). The UK study used a longitudinal design by conducting two surveys a year apart, with 118 participants in the first survey and 63 in the second. The authors found that 43% of PV adopters self-reported loadshifting behaviors in response to PV generation information, and that this behavioral change was most pronounced in households with someone home during the day and technologies that facilitated loadshifting (e.g. appliances with timers) (Keirstead, 2007). In terms of overall changes to electricity demand, the PV adopting households shaved approximately 6% off their final electricity consumption after adoption, mostly due to more efficient lighting and behavioral changes; a finding that the authors attribute to a greater awareness of energy issues (Keirstead, 2007). The Austrian study of PV adopters combines observed electricity consumption data with survey responses to find that electricity savings were present in the households with higher initial consumption, but that households with low-consumption increased their consumption after PV adoption (Haas et al., 1999). Furthermore, the data in Haas et al. (1999) show that 42% of solar adopting households also bought an efficient clothes washer and/or refrigerator. The joint purchase of these appliances and a PV system could signal a q-complementary relationship, as discussed in the next section. Contrary to these studies, Erge et al. (2001) did not find strong evidence of behavioral change and loadshifting in their study of PV adopting German households, though their analysis did not delve deeply into these aspects.

Interestingly, all of these studies implicitly assume that households who adopt PV change their electricity consumption habits *as a result* of their adoption, perhaps through a greater awareness and interest in energy issues. Here, we also consider the possibility of the converse linkage, namely that households with greater potential for loadshifting and self-consumption are more likely to adopt PV due to this potential.

The argument supporting point 2 above is rather straightforward; PV owning prosumers of electricity can usually save/earn more money by deploying their home-produced electricity in their home as opposed to selling the power back into the grid. Given that most domestic solar generators are tied into the electricity grid, and are not connected to household battery storage units, most PV owning households face a simple choice of using the power they produce immediately, or letting that power flow into the grid as an offset to their future electricity purchases or for an agreed upon price. The specifics of this arrangement can vary by country, state, and even household, based on the net metering laws, grid connection agreements, and any price supporting subsidy schemes that may be in place. In Austria, over 99% of residential PV installations are grid tied and thus are faced with the decision to use PV power at the time of generation or feed it into the grid via net-metering (Biermayr et al., 2018). The feed-in price received by residential solar power producers varies across Austrian energy providers, but lies between €0.03 and €0.15 per kWh, with the higher end feed-in prices only received for a fixed number of kWh sold per year (PV Austria, 2018). In contrast, the average residential end-use electricity price in 2017 for Austria was significantly higher at €0.20 per kWh (European Commission, 2018). This price difference makes it clear that for most Austrian residential PV unit owners the financially optimal way to deploy their solar power is through in home use, thereby directly offsetting their electricity purchases, as opposed to selling into the grid[1]. Thus, we hypothesize that owning dispatchable, electricity-intensive items that can be used to maximize the direct consumption of homemade solar power may increase the household utility gained from owning a PV unit.

The extent of this increase in utility will vary between different types of consumers depending on how their lifestyle (i.e. their loadshifting capacity) fits their actual PV generation curve. Klingler and Schuhmacher (2018) identify four different types of consumer types and show that the self-sufficiency rate of a PV owning households can reach 40% when no battery is present, and is between 56% and 67% when combined with battery storage. Klingler (2018) presents an average load profile of electric vehicle charging in Germany, which shows that EV-based residential load demands increase steadily from 10 am until peaking at 8 pm, suggesting that EV charging can be completed during daylight hours in some households. Klingler (2018) concludes that EV adoption increases the profitability of PV self-consumption, but that profits are increased if a battery is paired with the PV unit to additionally allow for EV charging in the evening. Ritte et al. (2012) show differences in the benefits of coupling EV and PV depending on commuters mobility needs and household daily energy use patterns. In their scenario analysis, commuters who take short to medium distance trips can supply between 25–67 % of their EV charging needs with a 5 kW residential solar unit. Hoarau and Perez (2018) also point at the potential time discrepancy between PV generation and actual electricity consumption and argue that PV and EV are “effectively synergistic technologies,” but their optimal use is still hampered by technological shortcomings, economic considerations, and ineffective public subsidy schemes that do not fully account for these potential synergies.

Another concern is that low energy use or empty residences during daylight times will not allow for large electricity consuming appliances to be deployed during times of solar production. The positive results with respect to loadshifting and behavioral change in energy usage of the field test studies discussed above (Wittenberg and Matthies, 2018; Haas et al., 1999; Hondo and Baba, 2010; Keirstead, 2007) suggest that this is not the case for all households. Furthermore, Fig. 2 shows, using the standard representative household load profile for Austria, that the average residential electricity load remains high during the daylight hours (9 am–5 pm) in both the summer and winter months. Taken together there is significant evidence that, at least some, Austrian households would be able to, and interested in, shifting appliance usage to allow for greater PV self-consumption.

This paper is the first to empirically consider direct linkages between PV adoption and the ownership of EV and other electricity-intensive appliances at the household level. The only study on this topic so far comes from Delmas et al. (2017), who research correlated demands for EVs and PV units in California. The authors use data at the census tract level to show that demands for these goods are correlated on the aggregate, and they interpret this as a sign of complementarity between the two goods. We extend this analysis to the European case of Austria, and use household-level data, which reveals the ownership and future purchase decisions of EVs, PV units, and other electricity-intensive household appliances, while

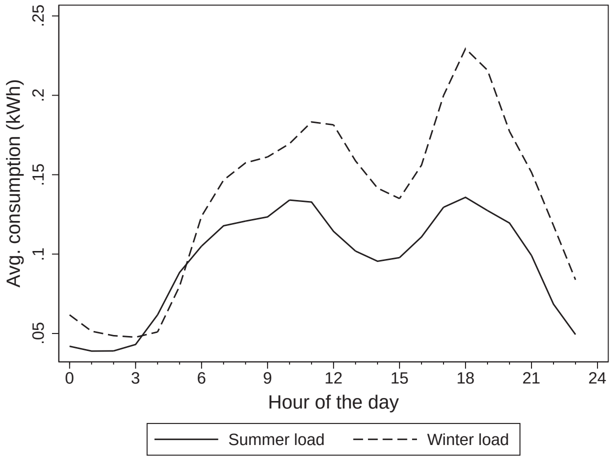

Fig. 2. Representative load profiles of Austrian households in winter (Dec.–Feb.) and summer (June–Aug.) months. Consumption values are normalized to a 1000 kWh annual load profile. Data come from the APCS Lastprofile 2018 dataset ‘H0’ values. The APCS is composed of many major Austrian utility companies that pool consumption data to build representative load profiles for various sectors.

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[1] The caveat to this statement is that there are a variety of subsidies for PV owners in place at the federal, state, and municipal levels in Austria, with the specific subsidies available to each PV owner varying by region, electricity provider, date of installation, and installed system size. Some of these subsidies include guaranteed feed-in-prices for selling power back into the grid (PV Austria, 2018). Thus, it is feasible that for some combinations of subsidy schemes a PV owner would be better off selling into the grid, or required to sell a certain amount into the grid, though we see no evidence that this situation occurs with any regularity in Austria or in our sample. In our sample, only 15% of PV owners report access to the Austrian national feed-in-tariff OeMAG.

controlling for household income, characteristics and environmental attitudes.

Aside from a general interest in low-carbon energy technology adoption and consumer behaviors, understanding these linkages is important in policymaking to be aware of any added benefits or unintended consequences of future EV/PV policies. PV and EV technology are the subjects of a vast number of incentive policies across the developed world (e.g. Crago and Chernyakhovskiy, 2017; North Carolina State University, 2017; RES Legal, 2012), thus any linkages in the household decisions to adopt PV and EV should be explored before large changes in policies come to pass, such as the planned expiration of the U.S. federal solar investment tax credit for residential installations in 2022. This paper constitutes a first step in exploring these potential linkages. We use the economic concept of q-complementarity to further motivate and define a potential relationship between PV adoption and the ownership of EV and other electricity-intensive home appliances. Using regression techniques, including a recursive bivariate probit which accounts for potential endogeneity, we find evidence that PV and EV adoption decisions are positively linked, which we posit is due to q-complementarity between these two goods. This finding suggests that policies which increase PV or EV adoption would have the added effect of increasing adoption of the complementary good.

2. Modeling linkages in adoption choice

In this work, we explore the hypothesis that PV installations and electricity-intensive home appliances are q-complements in household utility. If correct, this would mean that the adoption of PV increases the utility experienced by owning or purchasing an electricity-intensive appliance. In this section, we will focus on EV purchase as our q-complement of interest, as EVs are often highly electricity-intensive, and are also a good of interest in the literature on sustainable energy transition.

2.1. Theoretical model

The concept of q-complementarity was first espoused by Hicks in 1956 who stated that two goods are q-complements if the consumption of one good increases the marginal utility of consuming the other good (Hicks, 1956). Since then the concept of q-complements has mostly been overshadowed by its cousin, p-complements, which states that a negative relationship exists between the *price* of one good and the demand for its p-complement. The distinction between these concepts and a brief history of their development is discussed in Seidman (1989). In our case, we are not interested in relative prices, but in the relationship of utility and demand between PV installations and EV purchases, making q-complements the relevant concept. We aim to show that by starting with an assumption of q-complementarity, we arrive at a theoretical result where we expect demand between the two goods to be correlated, such that the probability of PV adoption is higher for households with EV, and vice versa.

Formally, consider a generalized representation of two goods, Y_1 and Y_2, and a numeraire commodity Z, where we can think of Y_1 as the number of PV installations and Y_2 as the number of EVs purchased. The goods Y_1 and Y_2 are q-complements if for some utility function $U(Y_1, Y_2, Z)$:

$$\frac{\partial^2 U}{\partial Y_1 \partial Y_2} > 0 \tag{1}$$

Meaning that the marginal utility gained from consumption of one more unit of Y_1 is higher when more units of Y_2 are also consumed. In our case the two goods in question, EVs purchased and PV systems installed, are large, expensive items that households will consume in small discrete quantities[2]. The q-complementarity condition in Eq. (1) may or may not be bi-directional, meaning that both goods could see increased utility as a result of owning the other good. In the theoretical model, we assume a bi-directional relationship, and investigate this assumption in the relationship of PV and EV with empirical models.

For a given household budget M, economic utility theory states that households will optimize and choose the most preferred bundle of goods that is financially feasible. For our two discrete goods Y_1, Y_2, with prices p_1 and p_2, the potential feasible bundles are limited to a discrete set S, e.g.:

$$(Y_1, Y_2, Z) \in S = \{(0,0,M), (1,0,M - p_1), (0,1,M - p_2), (1,1,M - p_1 - p_2)\} \tag{2}$$

Since PV and EV are big ticket items, the budget constraint will, in many cases, exclude bundles that include quantities of Y_1 and/or Y_2 that are greater than zero. For our purpose, we will restrict the considered utility space to S and specifically to those bundles in S where $Z > 0$, i.e. where not all budget is spent on EV and PV[3]. For a given household i, whose set of feasible bundles is exactly S, we can follow Train and Clifford (2007) and cast this problem in a discrete choice random utility framework, which allows us to represent household i's utility conditional on a given budget and price vector as a linear function[4]:

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

where $\hat{\epsilon}_i$ captures household-specific idiosyncrasy in utility levels for a given bundle. If the q-complementary condition from Eq. (1) holds there is an additional interaction term present in the utility functions, where $\alpha_{3i} > 0$ it represents the complementarity between the two goods. The household will make PV and EV adoption decisions that maximize $U_i(.)$ from their limited options given in Eq. (2). The options can be compared by differencing the utility functions for each option. For example, consider the case where the households decide to go from owning neither a PV nor an EV to purchasing both:

$$\begin{aligned}
&U_i(none) = U_i(0,0,Z_i|M_i,p_1,p_2) = \gamma_i(M_i) + \tilde{\epsilon}_i\\
&U_i(both) = U_i(1,1,Z_i|M_i,p_1,p_2) = \gamma_i(M_i - p_1 - p_2) + \alpha_{1i} + \alpha_{2i} + \alpha_{3i} + \bar{\epsilon}_i\\
&U_i(both) - U(none) = \alpha_{1i} + \alpha_{2i} + \alpha_{3i} - \gamma_i(p_1 + p_2) + (\bar{\epsilon}_i - \tilde{\epsilon}_i)
\end{aligned} \tag{4}$$

Here, $[U_i(both) - U_i(none)]$ represents the utility gained or lost by household i from choosing to purchase both PV and EV, as opposed to purchasing neither. The magnitude of the difference in utility is unimportant, however, the sign of the quantity $[U_i(both) - U_i(none)]$ determines if the household adopts both PV and EV or not, and we will observe adoption of both goods in households where $[U_i(both) - U_i(none)] > 0$. This decision is driven by the difference

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[2] Consumers can also choose the capacity (kW) of PV to install. However, we abstract from the capacity decision and just focus on the binary choice to adopt. This method is supported by past research that showed adoption and capacity were distinct choices in the case of California farmer's adoption decisions (Beckman and Xiarchos, 2013), and in the case of solar water heaters (Wang et al., 2017).

[3] Restricting consumer choice to at most one unit of a good is a useful assumption when considering complementary goods and their additivity, see for example Berry et al. (2017).

[4] We employ a linear utility function as in the random utility framework for ease of exposition and due to its compatibility with our econometric techniques described below.

between the marginal utility gained from having an EV and PV system in tandem $(\alpha_{1i} + \alpha_{2i} + \alpha_{3i})$, and the marginal utility of income that could have been spent on other goods $\gamma_i(p_1 + p_2)$.

Consumption choices may change over time as do prices of big ticket items, subsidy programs, household income and preferences as new information becomes available (Haas et al., 1999; Hondo and Baba, 2010; Keirstead, 2007), or due to household life-cycle development (Schelly, 2014). Hence, there can also exist a situation where the household i has already purchased, or decided to purchase, one of the items at a past date. In this situation, the relevant utility comparison between the feasible bundles is now conditional on $Y_{1i} = 1$ or $Y_{2i} = 1$, as shown in Eq. (5).

$$\begin{aligned}
&U_i(1, Z_i | Y_{1i} = 1, M_i - p_1, p_2) - U_i(0, Z_i | Y_{1i} = 1, M_i - p_1, p_2)\\
&= \alpha_{2i} + \alpha_{3i} - \gamma_i p_2 + (\dot{\epsilon}_i - \acute{\epsilon}_i)\\
&U_i(1, Z_i | Y_{2i} = 1, M_i - p_2, p_1) - U_i(0, Z_i | Y_{2i} = 1, M_i - p_2, p_1)\\
&= \alpha_{1i} + \alpha_{3i} - \gamma_i p_1 + (\ddot{\epsilon}_i - \grave{\epsilon}_i) \qquad (5)
\end{aligned}$$

For all three cases of adoption decisions in Eqs. (4) and (5), it is clear we would expect to see correlated demands for goods Y_{1i} and Y_{2i} when α_{3i} is positive. Specifically, $E[U_i(.)]$ is higher for bundles which include adoption of both items when α_{3i} takes higher values. In cases as in Eq. (5), for households that would not have adopted without the extra condition that $Y_{1i} = 1$ or $Y_{2i} = 1$, and the corresponding addition of $\alpha_{3i} > 0$ into the utility function may be pushed into an adoption decision. Thus, q-complementarity between goods should result in correlated demands.

2.2. Econometric model

The purpose of the econometric modeling exercise is to draw inference about the sign of α_3, the average of α_{3i} across the sample households. If q-complementarity exists between PV and electricity-intensive items, we should observe correlated demands for these goods, and thus can infer, with certain caveats, that $\alpha_3 > 0$. We begin with simple probit models for adoption probabilities that are commonly used in technology adoption literature (e.g. Hofacker, 2007; Wang et al., 2017; Nolan, 2010). In this case, we will model adoption probabilities of Y_{1i}, PV, and Y_{2i}, EV, using latent variables y^*_{1i} and y^*_{2i}, which represent the unobserved differences in utility between states of technology adoption and states of non-adoption, for each good respectively.

$$\begin{aligned}
&P[Y_{1i} = 1] = P[U_i(Y_{1i} = 1 | Y_{2i}, Z_i) - U_i(Y_{1i} = 0 | Y_{2i}, Z_i) > 0] = P[y^*_{1i} > 0]\\
&P[Y_{2i} = 1] = P[U_i(Y_{2i} = 1 | Y_{1i}, Z_i) - U_i(Y_{2i} = 0 | Y_{1i}, Z_i) > 0] = P[y^*_{2i} > 0] \qquad (6)
\end{aligned}$$

We posit a linear relationship between latent variables y^*_{1i}, y^*_{2i}, and observed household characteristics that may be relevant to each choice, $\mathbf{x}_{1i}$ and $\mathbf{x}_{2i}$, respectively. Assuming a normal distribution to the model error term, we obtain the probit specification shown in Eq. (7).

$$\begin{aligned}
&y^*_{si} = \mathbf{x}_{si}\boldsymbol{\beta} + \epsilon \quad \epsilon \sim N(0, 1)\\
&y_{si} = 1 \text{ if } y^*_{si} > 0\\
&y_{si} = 0 \text{ if } y^*_{si} < 0\\
&s \in \{1, 2\} \qquad (7)
\end{aligned}$$

where y_{si} are indicators for the observed ownership of PV or EV, taking a value of 1 if adoption has occurred. The $\boldsymbol{\beta}$ vector of slope coefficients will relate the effect of ownership of other big ticket items, and household characteristics, on adoption probabilities. We expect the coefficients relating big ticket item ownership to PV adoption to be positive if q-complementarity exists, indicating correlated demands for these items. Controlling for other household characteristics in $\mathbf{x}$, such as environmentalist attitudes and income, allows for stronger interpretations of any observed correlations in item ownership. However, causality between item ownership and PV/EV adoption can still not be inferred, as we generally do not observe the relative timing in decisions to purchase, or the relative prices, of these items.

To further establish a link between ownership of PV and EV, and provide stronger evidence regarding the q-complementarity hypothesis, we need to know the temporal relationship between adoption decisions, and also control for the possibility of endogenous decisions, either due to the simultaneous decision process shown in Eq. (4), or due to similar unobserved factors affecting both adoption decisions. In our sample, we have a large population of individuals who plan to purchase EVs, many of whom already own PV units. Thus, the temporal dimension of causality is established for these cases. To control for endogeneity, we employ a recursive bivariate probit model, where EV and PV ownership are endogenously determined. We again have two latent variables, y^*_{1i} and y^*_{2i}, with y_{1i} and y_{2i} being the ownership of PV and future plan to buy an EV, respectively. For y^*_{2i} the quantity represents respondent i's unobserved expectation of the change in utility from a state of no EV adoption to a future state of EV adoption, conditional on current PV ownership status (y_{1i}), similar to the decision shown in Eq. (5). The recursive bivariate probit framework following Maddala (1986) and Filippini et al. (2018) is:

$$\begin{aligned}
&y^*_{1i} = \boldsymbol{\beta}'_1\mathbf{x}_{1i} + \nu_{1i}, \quad y_{1i} = 1 \text{ if } y^*_{1i} > 1, \quad y_{1i} = 0 \text{ otherwise}\\
&y^*_{2i} = \delta y_{1i} + \boldsymbol{\beta}'_2\mathbf{x}_{2i} + \nu_{2i}, \quad y_{2i} = 1 \text{ if } y^*_{2i} > 1, \quad y_{2i} = 0 \text{ otherwise}\\
&[\nu_{1i}, \nu_{2i}] \sim \Phi[(0,0),(1,1),\zeta], \quad \zeta \in [-1, 1] \qquad (8)
\end{aligned}$$

whereΦ is the bivariate normal distribution, ν_{1i} and ν_{2i} are error terms that are assumed to be normal i.i.d, and $\zeta = Cov(\nu_{1i}, \nu_{2i})$ is an estimable parameter that allows for correlation in unobservables between the two choices. Furthermore, $\mathbf{x}_{1i}$ and $\mathbf{x}_{2i}$ are matrices of explanatory variables, with the stipulation that an additional variable(s) needs to be included in $\mathbf{x}_{1i}$ that is not in $\mathbf{x}_{2i}$, to ensure identification of the model (Mourifie and Meango, 2014). The vectors $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ hold the slope coefficients to be estimated that are associated with the explanatory variables. The model in Eq. (8) is estimated via the maximum likelihood method as described in Maddala (1986) and Greene (2012).

3. Data

Data for this analysis come from the LEAFS project survey of Austrian residential electricity customers from the states of Salzburg and Upper Austria. This survey was sent out via email to the mailing lists of customers of major energy providers in these two states. Participation in the survey was voluntary, and overall the survey attained a participation rate of 12%. Respondents were not directly compensated for their participation, but participation was encouraged through a randomized prize draw where about 1% of respondents received a small prize, such as gift vouchers. Average survey completion time was just under 10 min. The survey obtained socio-demographic information from respondents, including information on dwelling ownership, size and type of the dwelling, number of persons residing in the household, appliance ownership, income and questions about their energy behaviors and future intentions. In this paper, we use a subset of the collected data for empirical analysis that relates to appliance ownership and EV/PV adoption decisions, the selected variables are described in Table 1. Appliance ownership questions were included in the survey based on the expertise

Table 1
Variables used in the empirical analysis.

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 owns an EV or plans to buy one in next 5 years	0.29	0	0.45
battery_ownership	=1 if the household owns an electricity storage system	0.04	0	0.2
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 $<$ 1800 EUR	0.16	0	0.36
income_cat2	=1 if monthly HH net income 1800–2900 EUR	0.36	0	0.48
income_cat3	=1 if monthly HH net income 2900–4400 EUR	0.34	0	0.47
income_cat4	=1 if monthly HH net income $>$ 4400 EUR	0.15	0	0.35
high_environmentalism	=1 if HH believes environment/climate are "primarily" or "very" important in energy 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	26.30	26.12	7.37

N = 2541; HH = household.
*N = 2434 for this variable as the 107 HHs who already own EV are dropped.

of the utility company partners as to which appliances drive residential electricity usage and exhibit variation in ownership across households in Austria. All of the variables in Table 1 are constructed from survey responses with the exception of the last three variables, which are related to the area where the respondent lives.

The spatial variables, *UpperAT*, *population*, and *leftvoters*, are matched to respondents based on the self-reported postal code area in which the respondents live. The locations of our respondents are shown in Fig. 3 (a). This map shows the good geographic representativity achieved by the survey, with clusters of respondents near the large cities, and smaller groups of respondents from the smaller towns along the Alps to the South, and near the Czech and German borders to the North. Note that a few respondents fall outside the boundaries of the states of Salzburg and Upper Austria (the northwestern two regions with high concentrations of responses), this is due to the self-reported nature of respondent postal codes, where some respondents may have multiple residences, and thus are in the mailing lists of the energy providers, but currently live, or consider themselves residents, of a different Austrian state. From the initial 3202 completed survey responses 89 were dropped due to incorrect or incomplete postal codes, 567 were dropped due to respondents declining to provide income information, and 5 were dropped in cases where respondents reported living spaces below 20 m^2, which is thought to be mistaken input. The final estimation dataset contains 2541 complete responses, with 1720(67%) from the state of Upper Austria, and 821 (33%) from Salzburg. A spatial fixed effect variable for the state of residence (*UpperAT*) is included in all econometric models to account for variations in sampling frame, culture, politics, and geography between the two represented states.

Our sample of survey respondents is representative of some socio-demographic indicators in Upper Austria and Salzburg and deviates from others. This can be seen by comparing Table 2, which shows Austrian national and state level statistics, to Table 1, which shows our sample statistics. We note that the population ratio between Upper Austria and Salzburg are consistent with our survey sample that contains 67% Upper Austrian respondents. Mean net monthly income, is about €2100 in Salzburg and Upper Austria, which falls within the second income category from the survey (€1800–2900). However, the survey sample likely over-represents the higher income brackets within the two Austrian states, given that the 75% income quantile in these states is around €2600, whereas 50% of our sample reports incomes higher than this value. Similarly, the respondents in our sample are much more likely to own their own home, and live in a larger home, than the average citizen of Upper Austria and Salzburg. These differences from the population primarily reflect the sampling frame bias inherent in the data collection. Specifically, the energy companies that sent out the surveys to their customers primarily operate in the rural regions, with other energy companies often handling provision within the cities. Thus, the sample that we drew from is more likely to be sub-urban or rural dwellers with larger homes, and slightly higher incomes. Accordingly, we would expect that our survey sample over-represents households with EVs and PV units, though it is not possible to verify this with national statistics[5]. However, our survey sample still exhibits variation along socio-demographic and appliance ownership dimensions, and thus can give valid insights into household purchase decisions, but out-of-sample generalizations should be made with note of the sampling frame bias.

In this paper, we are primarily interested in the appliance purchase decisions of households, particularly the adoption of PV and EV. In the survey, the question regarding EV ownership simply asked "Do you own an electric car?"[6] This is a general term for plug-in, electricity consuming vehicles that encompasses the more specific terms, such as 'battery electric vehicle' or 'hybrid-electric vehicle'. While other work has shown that the purchase decision between specific types and brands of EV is a function of household characteristics (Delmas et al., 2017; Hidrue et al., 2011), in this paper, we concern ourselves with the more general question of households choosing to adopt or not adopt this type of e-mobility solution.

The second question of primary interest regarding PV unit ownership, specified solar electricity generators as opposed to solar water

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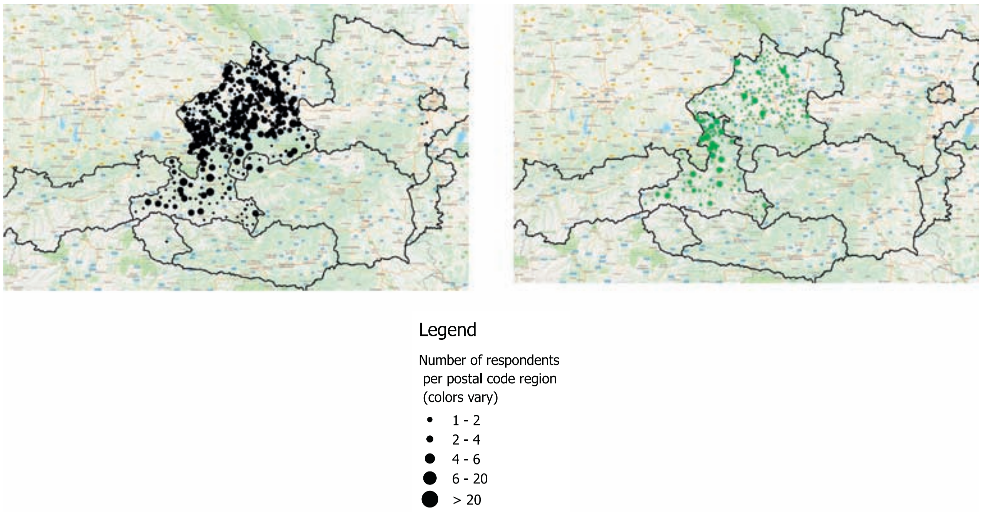
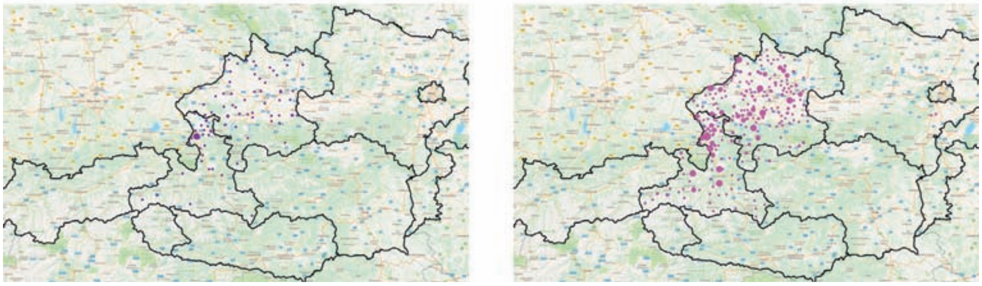
[5] We would need statistics on the number of *households* with PV units and EVs, which does not exist in Austria. Instead, we show comparative statistics in Table 2, which show that solar power is somewhat prevalent in the electricity mix (a mix with 85% fixed as hydro generation), while EVs still only make up a small proportion (2.4%) of the total car stock.

[6] In original German: "Besitzen Sie ein Elektroauto?"


(a) Survey respondents

(b) Current PV owners


(c) Current EV owners

(d) Households who plan an EV purchase within 5 years

Fig. 3. Survey respondents aggregated by postal code region.

Table 2
Austrian national and state level statistics relevant to the survey sample.

Quantity	Austria	Upper Austria	Salzburg	Source
Proportion of EVs in car stock	2.4%	NA	NA	statistik.at “Fahrzeug-Bestand am 31. August 2018”
Proportion of solar power in electricity mix	1.9%	NA	NA	PV austria “PV Branche in Zahlen 2017”
Mean net monthly income (Euros)	2158	2152	2095	statistik.at “Nettomonatseinkommen Jaresdurchschnitt 2016”
Population	8,811,782	1,472,422	551,863	statistik.at “Bevoelkerung Oesterreich 2017”
Home ownership rate	47.8%	51.3%	51.7%	statistik.at “Eigentumsquote 2017”
Mean living space per dwelling (sq. meters)	99.6	106.8	96.3	statistik.at “Wohnungsgroesse 2017”

heaters, or other solar power technologies. The third question of primary interest asked if respondents were planning to purchase an EV in the next 5 years[7], from which we construct the variable *EV_plan*. The responses to the ownership of PV, EV and future plans to purchase EV were aggregated at the postal code level, and are shown cartographically in Fig. 3 (b) –(d). In these maps, larger circles indicate that more respondents in that postal code region reported a positive response to the referenced question. We see from Fig. 3 (b), that PV ownership is relatively homogenized across the sample region, with a similar spatial distribution of PV owners as the overall distribution of respondents. Fig. 3 (c) highlights the low number of current EV owners in the sample who appear to be clustered around the city of Salzburg in Salzburg state, and more evenly distributed in the state of Upper Austria. Few respondents who live in the southern alpine region own an EV, perhaps due to low numbers of charging stations, or concerns over EV performance in a cold weather, mountain environment. Finally, panel maps (d) shows the spatial distribution of planned EV purchases, which we find to be evenly distributed throughout respondents, with a spatial correlation coefficient of 0.93 between Fig. 3 panels (a) and (d), and a spatial correlation coefficient of 0.79 between Fig. 3 panels (b) and (d), suggesting a spatial link between PV ownership and future EV adoption.

In our sample of Austrian households, we observe a high rate of PV unit ownership (25%), and a relatively low rate of EV ownership (4.2%), with 11% of PV owners having already purchased an EV. The survey also includes a question which asked those respondents who do not already own a PV unit if they planned to buy one in the next year, with few respondents (60, 3%) stating that they plan this purchase. In contrast, only 4.2% of the sample has already adopted an EV, with 25% of those who have not yet adopted stating that they plan to purchase an EV within the next 5 years. Thus, from the data, it appears that EV adoption is temporally lagging behind PV adoption, at least in Austria. This is likely due to the oft-noted barriers

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[7] In original German: “Haben Sie vor sich in den kommenden 5 Jahren ein Elektroauto anzuschaffen?”

Table 3
Correlation coefficients between household appliance ownership variables.

	*PV_*	*EV_*	*dryer_*	*pool_*	*aquarium_*	*waterbed_*	*sauna_*
PV_ownership	1.000						
EV_ownership	0.226	1.000					
dryer_ownership	0.126	0.025	1.000				
pool_ownership	0.081	0.053	0.177	1.000			
aquarium_ownership	0.037	−0.015	0.075	0.060	1.000		
waterbed_ownership	0.030	0.016	0.077	0.132	0.071	1.000	
sauna_ownership	0.113	0.059	0.139	0.241	0.014	0.072	1.000

N = 2541; Variables are described in Table 1.

Table 4
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***	(0.033)		
PV_ownership			0.071***	(0.010)
battery_ownership			0.0296**	(0.013)
electric_heat	0.0961***	(0.017)	−0.0111	(0.009)
dryer_ownership	0.0279*	(0.017)	−0.0061	(0.008)
pool_ownership	0.0372*	(0.020)	0.0042	(0.009)
aquarium_ownership	0.0189	(0.035)	−0.0278	(0.021)
waterbed_ownership	0.0180	(0.039)	0.0178	(0.019)
sauna_ownership	0.0417**	(0.017)	0.00751	(0.008)
owns_home	0.0800**	(0.034)	0.00108	(0.016)
livingspace_home	0.000537***	(0.000)	0.00002	(0.000)
singlefamily_home	0.107***	(0.024)	−0.00693	(0.011)
household_size	0.0347***	(0.007)	−0.00025	(0.003)
income_cat1 (<1800)	–	–	–	–
income_cat2 (1800–2900)	0.0213	(0.025)	0.00638	(0.009)
income_cat3 (2900–4400)	−0.00764	(0.025)	0.0279***	(0.011)
income_cat4 (>4400)	−0.00760	(0.029)	0.0320**	(0.014)
high_environmentalism	0.0376**	(0.019)	0.0189*	(0.011)
UpperAT	−0.248***	(0.018)	0.0107	(0.009)
population (1000's)	−0.0007***	(0.000)	0.00008	(0.000)
leftvoters (%)	−0.005***	(0.001)	0.0002	(0.001)
N		2541		2541
Pseudo R-sq.		0.2		0.15

N = 2541; $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$; only PV owners own battery storage, so the *battery_ownership* variable must be excluded from the *PV_ownership* model due to lack of variation.

to EV adoption such as lack of charging infrastructure, high costs, and lack of trust in new technology (Biresselioglu et al., 2018). With a known timing between EV and PV purchases in these cases, we can establish a stronger link between PV ownership and future purchases of EVs, while accounting for any possible endogeneity in these decisions using the model in Eq. (8). This sort of investigation was not possible in the previous work of Delmas et al. (2017) since their sample included only individuals who have an EV, as opposed to our mixed group of EV owners and non-EV owners.

As a first look at the possibly joint decision between PV, EV, and other electricity-intensive appliance ownership, we calculate the correlations in ownership of these items for our sample, as shown in Table 3. We see that PV ownership is positively correlated with ownership of all 6 electricity-intensive goods tested[8]. The strongest correlation of PV ownership is with EV ownership, at 0.226, with the next strongest being dryer ownership, at 0.126, and then sauna ownership, at 0.113. Saunas enjoy popularity in Austrian culture, as shown by the 33% of households in our sample that own one, as a way to relax and warm up in the winter. In contrast to PV ownership, we see that EV ownership exhibits low levels of correlation with the other electricity-intensive goods. This suggests that our q-complementarity hypothesis between PV and electricity-intensive appliances, due to increased loadshifting, offsetting, and environmental efficacy potential, may be valid. The regression modeling presented in the next section aims to prove that PV ownership is still correlated with these other goods, even after accounting for household income, characteristics, and attitudes.

4. Predictors of PV and EV adoption

To begin the empirical analysis, we model PV and EV ownership probabilities as a function of the explanatory variables shown in Table 1. We consider only a binary decision to adopt vs. not adopt a PV or EV unit. Investigating linkages in adoption scale, i.e. how many solar panels to install *vis a vis* how many EVs to buy, is left to future research. This choice is supported by past research which has shown that the choice to adopt PV is systematically different from the scale of PV adoption (Beckman and Xiarchos, 2013; Wang et al., 2017). The marginal effect of explanatory variables on adoption probabilities, estimated via probit models in Eq. (7), are given in Table 4.

The results show strong correlation between EV and PV ownership, even after accounting for individual and communal attitudes (*high_environmentalism*, *leftvoters*), and household incomes. This correlation is substantial, with a 31% increase in the probability of owning a PV if an EV is also owned, and bi-directional, with a 7.1% higher chance to own EV if PV is owned. This is the first evidence that q-complementarity may exist between EV and PV technologies. Furthermore, PV ownership is positively correlated with the ownership of some electricity-intensive appliances, namely electric

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[8] Additionally, 4% of the sample report owning a battery storage system — all of whom also own PV units.

heating systems, electric dryers, pools (which usually include pumps and/or heaters), and saunas. Ownership of aquariums and waterbeds also show a weak positive correlation with PV ownership that is not statistically significant at the 10% level. These results suggest that households with big ticket, electricity-intensive items are more likely to adopt PV, even after controlling for income effects, and vice-versa, suggesting these items may be q-complements with PV systems as they give the potential for higher self-consumption and loadshifting to times of higher PV production.

Larger households, both in terms of number of persons and living space, are more likely to adopt PV, probably due to them having higher energy costs to be offset by PV prosumption, and more roof space to install PV. Ownership of one's residence and living in a detached building both increase PV adoption probability, likely through the easier contracting, and permitting associated with these living arrangements. However, similar to Mills and Schleich (2009)'s results for solar-thermal adoption in German households, we do not find strong evidence that PV adoption varies across income strata in Austria. Nevertheless, higher income groups are more likely to purchase EVs, specifically households that make over €2900 net per month. Self-reported environmental attitudes are positively associated with adoption of both PV and EV, as expected. Furthermore, households in areas with higher populations have a slightly lower solar adoption probability, possibly due to urban-rural factors. The ownership of a battery storage system coupled to the PV unit is also positively correlated with EV adoption, perhaps due to the greater ease of loadshifting and solar energy self-consumption afforded by coupling a battery with an EV (Klingler, 2018). Finally, we find that the percent of 'left'-leaning voters in the area has a small decreasing effect on household PV adoption probability. This could be due to the fact that in Austria, where the majority of political groups support sustainability, leftist politics engages more strongly with social programs than with environmental programs. Thus, the negative coefficient observed for the variable *leftvoters* on PV installation probability could be due to local governments in areas with more left voters supporting social initiatives, like subsidized daycare, over environmental ones, like PV purchasing collectives.

4.1. EVs as q-complements to PV ownership

The next step in the empirical analysis is to try and establish a stronger link between PV and EV purchase decisions by considering the temporal dimension. As discussed previously, the data show very few respondents currently own an EV (107), but many plan to buy one in the next 5 years (616), and of these 616 future EV purchasers 250 currently own a PV unit while 366 do not. This is a relatively high proportion of PV owners in the future EV purchasers group, considering that only 25% of the sample currently owns a PV unit. The question addressed here is whether there is a higher likelihood of future EV purchase for those that already own PV, which we would interpret as evidence of q-complementarity between these two goods. Controlling for covariates, such as income and environmentalist attitudes, as well as any endogeneity between PV and EV purchase decisions is thus critical. Note that, as in any context where intentions are collected, hypothetical bias is a concern in the responses related to planned purchases of EV. In this case, literature suggests that the low number of current EV adopters compared to the high number of future adopters is driven by the novelty of the technology and physical adoption barriers, most notably lack of fast charging infrastructure and charging-enabled parking spaces in apartments and garages (Biresselioglu et al., 2018). Thus, the true future behavior of our planned adopters may be driven in part by the removal of such physical barriers. Nevertheless, the results of this section must be interpreted with care for potential hypothetical bias.

To control for potential endogeneity between PV and EV adoption decisions, we use a recursive bivariate probit specification where PV ownership is endogenously determined.[9] The form of this model is shown in Eq. (8), where the main dependent variable of interest is *EV_plan*, described in Table 1. The variables whose partial effects are shown in Table 5 are contained in the matrix $\mathbf{x}_2$ and explain the probability that a respondent plans to purchase an EV. The secondary, or 'selection', equation in the bivariate probit model has *PV_ownership* as the dependent variable and contains all variables in $\mathbf{x}_2$, as well as indicators for the household's ownership of other electricity-intensive appliances. The addition of these indicator variables satisfies the necessary exclusion restriction to identify the bivariate probit system (Mourifie and Meango, 2014; Han and Vytlacil, 2017). The full output of the recursive bivariate probit model is given in Table 6, in the Appendix.

Table 5
Partial effects from recursive bivariate probit model on future planned EV purchase with PV ownership endogenously determined.

Variable	Marg. Eff	Std. Err.	Z-stat.	Prob>Z
PV_ownership	0.2094**	0.101	2.07	0.04
battery_ownership	0.0454	0.085	0.54	0.592
owns_home	0.0425	0.032	1.34	0.18
livingspace_home	0.0002	0.000	1.04	0.30
singlefamily_home	−0.0293	0.027	−1.11	0.27
household_size	0.0006	0.008	0.07	0.95
income_cat2 (1800–2900)	0.0739***	0.024	3.06	0.00
income_cat3 (2900–4400)	0.0918***	0.025	3.69	0.00
income_cat4 (>4400)	0.1625***	0.032	5.02	0.00
high_environmentalism	0.0613***	0.022	2.78	0.01
UpperAT	−0.0074	0.036	−0.21	0.84
population (1000's)	0.0005**	0.000	2.02	0.04
leftvoters (%)	−0.0001	0.001	−0.08	0.94

Sample excludes current EV owning households; N = 2434; *p<0.1, **p<0.05, ***p<0.01.

The partial effects on the intention to purchase EV in the next 5 years are shown in Table 5. The partial effect of the j^{th} variable in $\mathbf{x}_2$ takes the form:

$$\frac{\partial E[y_2|\mathbf{x}_2]}{\partial x_j} = \frac{\partial P[y_2 = 1|\mathbf{x}_2]}{\partial x_j} \tag{9}$$

We see from the model output that PV owners have an 21% higher chance of planning to purchase EV in the next 5 years. We also find that higher income families (> €1800 net monthly income) are more likely to be planned purchasers, naturally due to the high initial cost of EV and personal automobiles in general. Environmentalist attitudes are also shown to be positive drivers of EV purchases, with a 6% higher chance of EV adoption for households who self-reported that environmental issues were very important to them in energy considerations. Interestingly, battery owning PV households do not show a stronger intention to adopt EVs than those that do not own batteries, perhaps due to the possibility of future EV adopters using their EVs in lieu of stationary batteries for storing solar power — a technology coupling that is currently under development (Mehrjerdi and Rakhshani, 2019). The results also show that households living in areas with higher populations are more likely to adopt an EV, probably due to lower distances driven on average and higher density of charging infrastructure in higher population areas, which have been shown to be barriers to EV adoption (Biresselioglu et al., 2018).

Of all the tested drivers for plans to adopt EV, the largest marginal effect is from current PV ownership. This finding suggests a strong

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[9] We explicitly test for endogeneity between *PV_ownership* and *EV_plan* using a Wald test with a null hypothesis that $\zeta = 0$. Following Filippini et al. (2018), who note that this test is structurally inappropriate in the recursive bivariate probit, we complete this test using an auxiliary bivariate probit model without recursive structure that contains all explanatory variables shown in Table 4. We reject the null with a Chi^2-stat of 126.9 and a p-value of 0.00001, suggesting that the tested variables are endogenous and that a bivariate approach is justified.

linkage between PV ownership and future purchase decisions that reflect the conditional decision process shown in Eq. (5). Namely, that with a PV unit already purchased, a subsequent intention to purchase EV technology is 21% more likely than if a PV unit is not already owned. Importantly, using the recursive bivariate probit specification and a suite of control variables, this finding is robust to endogeneity between PV and EV decisions, income levels, and environmentalist attitudes, providing evidence for q-complementarity between EVs and PV units.

5. Conclusions

This paper investigates the potential for linkages between PV ownership and electricity-intensive home appliances, most notably EVs. Linkages between PV units and these goods could manifest as q-complementarity, whereby ownership of PV increases the benefits from owning electricity-intensive appliances and EV, and/or vice versa. The conditions and ramifications of q-complementarity are shown using economic utility theory, with a key point being that q-complementarity between goods implies that correlated demands between these goods should be observed.

As a first novel output, we find that PV ownership is in fact correlated with the ownership of big ticket, electricity-intensive household goods including electric heaters, dryers, saunas, pools, and EVs, after controlling for income and environmental-attitude effects. This finding suggests that PV units may be q-complements to the listed goods due to the increased perception of environmental efficacy and potential for loadshifting/offsetting electricity consumption in households who own these big ticket items. Our findings with respect to PV adoption also confirm past literature in showing that environmentalist attitudes, home ownership, and household size positively influence adoption probability (Wang et al., 2017; Noll et al., 2014).

As a second novel output, we show a positive relationship between household PV ownership with EV ownership, and with the intention to purchase EV in the next 5 years. Notice that while PV ownership has an effect on current EV ownership, with an estimated 7% increase in EV ownership probability, it has a relatively strong effect on the intention for future EV adoption, with an estimated 21% increase in EV adoption intention probability[10]. This difference could signify an increased interest in energy issues and sustainable energy practices following household PV adoption, as discussed by prior research (Ryghaug et al., 2018; Wittenberg and Matthies, 2018). Nevertheless, the findings support our hypothesis of q-complementarity, namely that having a PV unit may increase the marginal utility gained from purchasing an EV.

The evidence presented in this paper supports a direct linkage between household PV and EV adoption decisions, as suggested by the aggregated analysis in Delmas et al. (2017), which we posit is due to q-complementarity between these goods. The existence of such a linkage implies that policy decisions regarding PV and EV are, in turn, linked. Thus, policies that support or dissuade PV or EV adoption could have unintended consequences on the adoption of the latter good. Specifically, we find that policies which increase PV adoption, such as subsidies and rebates (Crago and Chernyakhovskiy, 2017), would have the added benefit of increasing EV adoption in the medium-term (within 5 years). Along with suggesting a linked policy environment between PV and EVs, this finding has grid-level implications for the transition to a low-carbon, decentralized, energy system. Namely, that renewable power integration concepts, such as the ‘vehicle-to-grid’ idea of using EVs as supplementary batteries to store intermittent renewable-sourced electricity (e.g. Mehrjerdi and Rakhshani, 2019; Noel et al., 2019) may be especially relevant in the context of single households that own both a PV unit and an EV. Conversely, our findings with respect to other electricity-intensive household items (electric heating systems, dryers, pools, and saunas) suggest that any policy which decreases the demand for these goods, perhaps e.g. higher energy-consumption or sales taxes, would have the unintended consequence of decreasing PV adoption rates in households. Given the linkages between these goods shown in this paper and the high number of PV, EV, and energy-related policies under consideration, further research into these linkages is warranted to better understand any potential added benefits, unintended consequences, or equity effects of proposed policy changes.

Appendix A

Table 6
Coefficient estimates from recursive bivariate Probit model on EV ownership or future planned EV purchase with PV ownership endogenously determined.

	Main equation: *EV_plan* is dependent variable	
Variable	Coefficient	Std. Err.
PV_ownership	0.709**	(0.360)
battery_ownership	0.154	(0.283)
owns_home	0.144	(0.106)
livingspace_home	0.000545	(0.000516)
singlefamily_home	−0.0992	(0.0909)
household_size	0.00198	(0.0286)
income_cat2 (1800–2900)	0.276***	(0.0945)
income_cat3 (2900–4400)	0.335***	(0.0957)
income_cat4 (>4400)	0.553***	(0.111)
high_environmentalism	0.207***	(0.0736)
UpperAT	−0.0251	(0.121)
population (1000's)	0.00176**	(0.000891)
leftvoters (%)	−0.000381	(0.00475)
constant	−1.474***	(0.178)
	Secondary equation: *PV_ownership* is dependent variable	
	Coefficient	Std. Err.
battery_ownership	7.033***	(0.105)
owns_home	0.286*	(0.147)
livingspace_home	0.00211***	(0.000480)
singlefamily_home	0.449***	(0.109)
household_size	0.125***	(0.0288)
electric_heat	0.362***	(0.0728)
dryer_ownership	0.0906	(0.0713)
pool_ownership	0.155*	(0.0942)
aquarium_ownership	0.0455	(0.147)
waterbed_ownership	0.0884	(0.163)
sauna_ownership	0.173**	(0.0758)
income_cat2 (1800–2900)	0.0382	(0.104)
income_cat3 (2900–4400)	−0.0229	(0.104)
income_cat4 (>4400)	−0.0478	(0.124)
high_environmentalism	0.138*	(0.0778)
UpperAT	−0.897***	(0.0854)
population (1000's)	−0.00271**	(0.00114)
leftvoters (%)	−0.0207***	(0.00500)
constant	−1.407***	(0.198)

N = 2434.
* p<0.1.
** p<0.05.
*** p<0.01.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2019.08.004.

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[10] These marginal effect estimates are significantly different from each other at the 1% level of significance with a *t*-statistic of 8.7.

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