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Abstract

Within the regulation of net purchasing, investment incentives for residential PV depend on the remuneration for grid feed-in and the consumption costs that households can save by self-consumption. Network tariffs constitute a substantial part of these consumption costs. We use postcode-level data for Germany between 2009 and 2017 and exploit the regional heterogeneity of network tariffs to investigate whether they encourage to invest in PV installations and evaluate how the nonlinear tariff structure impacts residential PV adoption. Our results show that network tariffs do impact PV adoption. The effect has increased in recent years when self-consumption has become financially more attractive, and the results confirm the expectation that PV investments are driven by the volumetric tariff. Policy reforms that alter the share between the price components are, thus, likely to affect residential PV adoption. Further, with self-consumption becoming a key incentive, price signals can effectively support the coordination of electricity demand and supply in Germany.

Keywords: Network tariffs, PV investments, self-consumption, price perception, panel data, prosumer, non-linear prices

JEL classification: C33, D12, L51, Q42

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1. Introduction

Solar photovoltaic (PV) is generally expected to have a substantial share in the future electricity generation mix around the globe (IEA, 2020). In Germany, residential PV systems already count for around 1.2 million installations in 2020 (Bundesnetzagentur, 2021b). These PV systems are typically installed by individual households and, thus, distributed decentrally. To limit network expansion and reduce congestion costs, an efficient coordination of these investments is essential.

Recent findings suggest that economic factors are among the main drivers for PV adoption in the residential sector (e.g. Jacksohn et al., 2019). In principle, households can use the self-generated PV electricity to either feed it into the grid or replace electricity consumption from the grid. The profitability of these options depends on the regulatory framework. In Germany, a net purchasing system is in place for residential PV installations, which is also the predominant metering scheme in Europe (Gautier et al., 2018). That is, grid feed-in and grid consumption are metered separately and billed at two different prices. The remuneration of grid feed-in is based on the feed-in tariff, which is the main subsidy for residential PV in Germany, granted under the Renewable Energy Sources Act (EEG.). The value of self-consumption depends on the consumption costs, which households can reduce for each kilowatt-hour (kWh) of grid consumption substituted with self-generated PV electricity.

Higher tariffs for grid consumption increase the consumption costs of the household and raise the incentive for self-consumption and residential PV installations. This relationship is unambiguous under net metering, where grid feed-in and grid consumption are billed at the same price (c.f. Gautier and Jacqmin, 2020). Under net purchasing, the same rationale should apply, although the incentive structure also depends on the remuneration for grid feed-in. In particular, the effect should increase the more profitable self-consumption is compared to the revenue from grid feed-in (c.f. Jägemann et al., 2013).

Additionally, tariffs follow a nonlinear pricing schedule. The investment decision should be incentivized only by the volumetric price rather than the fixed price component or an average price calculated from both. Empirical findings suggest that consumers confuse nonlinear price schedules, which contrasts with the theoretical expectation (Ito, 2014). Such an effect would raise concerns regarding the effect of regulatory changes in electricity price components on residential PV installations. In Germany, for example, reform proposals for the network tariff system plan to shift network costs from predominantly volumetric network tariffs to a more substantial share of fixed network tariffs. Other proposals aim for a change in the EEG-levy that is currently paid exclusively on a volumetric basis. Knowing whether and how consumers respond to the different price components is crucial to assess the consequences of such policy reforms on PV adoption.

We empirically investigate whether and how price signals impact the adoption of residential PV installations in Germany. More specifically, we analyze the impact of network tariffs on PV adoption and exploit the fact that network tariffs are a considerable part of retail tariffs and the decisive driver for their regional variation. The heterogeneity of network tariffs allows us to identify the impact of price signals on a high regional resolution. In contrast, the other components of the retail tariff depend on markets and regulations that are equal across Germany. We use a panel data set of PV installations, network tariffs, and socioeconomic covariates on postcode level covering the years of 2009-2017 and apply a Poisson quasi-maximum likelihood estimator (PQMLE) with fixed effects to capture unobserved heterogeneity across regions and time.

We find evidence that network tariffs significantly impact PV investments across Germany. An increase in network tariffs by one eurocent per kWh is estimated to increase PV installations by 5.8 %, all else equal. This effect has grown, supporting the hypothesis that the incentive for self-consumption has increased over time. Furthermore, it is indeed the volumetric network tariff that impacts PV adoption rather than the average price. Our results provide valuable insights into the driving forces of residential PV adoption in Germany, which allows evaluating upcoming policy reforms regarding the regional allocation of PV installations and the structure of electricity prices.

The paper is organized as follows. Section 2 provides an overview of the empirical literature on residential PV adoption. Section 3 outlines the policy framework and the economic rationale for investment in residential PV installations in Germany. Section 4 introduces the empirical strategy while section 5 presents our panel data set. Our results are shown and discussed in section 6 and we discuss our findings and conclude in section 7.

2. Literature review

Our analysis contributes to two streams of the literature: first, the drivers of residential PV expansion focusing on Germany, and second, the impact of nonlinear tariff structures on investment decisions in the residential energy sector.

The main drivers for residential PV investments can be classified by socio- and techno-economic factors, behavioral factors, and economic factors.[1] The first and most extensively researched category are socioeconomic factors such as education, per capita income, environmental awareness, and techno-economic factors, such as solar irradiance and specific house characteristics. Schaffer and Brun (2015) conduct a comprehensive analysis on the drivers for adopting residential PV in Germany between 1991 and 2012. They find strong effects for solar irradiance, house density, homeownership, and per capita income, while the environmental awareness hardly affects PV investments. Subsequent studies, for example, Dharshing (2017), Baginski and Weber (2019), Jacksohn et al. (2019) and Gutsche et al. (2020), generally confirm these findings: environmental awareness has only little explanatory power, while the other socio- and techno-economic factors are important drivers of residential PV adoption in Germany.

Second, behavioral factors, such as myopia, inertia, or peer effects, are also likely to drive PV adoption in the residential sector. For example, regarding peer effects, i.e., the impact of previously installed PV in a surrounding area on the current investment decision of an individual household, findings in the empirical literature are mixed. In their seminal work, Bollinger and Gillingham (2012) examine peer effects on residential PV expansion in the US and find a significant impact. Rode and Weber (2016) conduct a similar analysis for Germany and confirm the impact of imitative adoption behavior. Though Baginski and Weber (2019) also find regional dependencies in their analysis, social imitation does not seem to be the main driver of the regional spillover effects. Similarly, Rode et al. (2020) find that the impact of previously installed PV on current adoption decreases over time and might be mistaken with the regional concentration of craft skills or solar initiatives.

[1] Comprehensive reviews on the adoption of building-scale renewable energy systems in European countries can be found in, for example, Heiskanen and Matschoss (2017) and Selvakkumaran and Ahlgren (2019).

The third category contains literature on the influence of economic factors, i.e., expected costs and revenues of the PV installation.[2] We observe a growing research interest regarding the economic factors due to two simultaneous developments. First, Palm (2020) suggests that in the first stage of the diffusion process, early adopters have fewer concerns for costs or concrete financial benefits. In contrast, in the later stages, the economic factors become more decisive. Hence, the impact of socioeconomic and behavioral factors on PV investments should decrease over time as these factors become less pivotal during the diffusion process of new technologies. Second, in the early years of PV expansion in Germany, a PV installation has been financially attractive mainly due to the feed-in tariffs granted as a subsidy for PV deployment. Ossenbrink (2017), and Germeshausen (2018) analyze the impact of feed-in tariffs in Germany and, in particular, the impact of (changes in) the policy framework on PV adoption. Jacksohn et al. (2019) analyze the impact of the costs of PV panels and revenues from feed-in tariffs in Germany from 2008 to 2015 on the individual household level. They find that these economic factors mainly drive the investment decisions in PV installations and solar thermal facilities.

With the increasing attraction of self-consumption, the economic rationale of residential PV installations is further influenced by the costs for electricity consumption and, therefore, not only by the feed-in tariff but also by the retail tariff. Klein and Deissenroth (2017) show that the overall German residential PV expansion is impacted by the anticipation of profitability, including both feed-in and retail tariffs in their analysis. Sahari (2019) analyzes the choice of heating systems in Finland. She finds a significant impact of electricity prices on long-term technology choices. Further and closest to our analysis, Gautier and Jacqmin (2020) analyze the impact of volumetric network tariffs on PV investments under a net metering system in Wallonia. They find a positive and significant effect of network tariffs on PV installations. In a similar vein, de Freitas (2020) analyzes PV investments in Brazil. Both regions currently apply net metering systems, where grid feed-in and self-consumption are both valued at the retail tariff. Therefore, higher retail tariffs should encourage higher PV investments. In a net purchasing system, the incentive is two-fold and depends on the remuneration for grid feed-in, which is determined separately (see section 3).

[2] Intuitively, cost and revenues also depend on techno-economic factors, like irradiance. However, we think of economic factors as monetary metrics.

Moreover, we extend the analysis of price signals by examining how the nonlinear tariff structure influences investment decisions. In his seminal work, Ito (2014) analyzes the price perception of consumers in US electricity markets. His results suggest that consumers are short-sighted in their response to electricity prices by deciding on their electricity bill of the past rather than current tariffs or future expectations. Further, Ito (2014) examines the impact of nonlinear multi-tier tariffs on electricity consumption, and Shaffer (2020) conducts a similar analysis for British Colombia. The authors analyze whether consumers respond to nonlinear tariffs in the way microeconomic theory suggests, i.e., whether they respond to the marginal price rather than the fixed or an average price. Both find that consumers respond to average rather than marginal prices, which contrasts with the theoretical expectation. However, a further analysis by Ito and Zhang (2020) for heating usage in China finds that consumers do indeed respond to the marginal price in the context of a simpler tariff form, i.e., a two-part tariff.

To the best of our knowledge, we are the first to empirically analyze the impact of price signals on PV adoption in a net purchasing system. We use the regional variation in network tariffs in Germany to investigate whether and how prices impact PV investments. We examine whether the incentives for self-consumption have become more relevant in recent years and conduct the first empirical study that analyzes how the price components of a nonlinear tariff impact residential PV adoption.

3. Residential PV in Germany: policy framework and investment incentives

PV installations enable individual households to generate their own electricity so that they no longer participate in the market only as consumers.[3] To illustrate the economic rationale behind residential PV adoption in Germany, we derive the microeconomic foundation of the investment incentives for an individual household. The regulatory framework in Germany is a net purchasing system. In contrast to a net metering system, where one single price for electricity consumption from the grid (imports) and grid feed-in (exports) exists, these two options are measured separately (c.f. Gautier et al., 2018).

[3] As households with PV installations both produce and consume electricity, the term prosumer has also been established. Prosumers are of general interest in recent literature, seeking to understand their decision-making and how regulatory policies impact them in more detail, (e.g. Gautier et al., 2018).

The PV installation offers two options for the household how the self-generated electricity (q_{PV}) can be used:

$$q_{PV} = q_{togrid} + q_{self} \tag{1}$$

The household can feed the electricity into the grid (q_{togrid}) or use it for self-consumption (q_{self}), i.e., substitute electricity consumption that is otherwise imported from the grid (d_{total}).[4] We structure the economic incentives by analyzing the net present value (NPV)[5] of the PV installation in equation (2):

$$NPV = -C_I + \sum_{t=0}^{T} \frac{R(q_{togrid}) - C(d_{total} - q_{self}) - c_{OM}}{(1+r)^t} \tag{2}$$

One-time costs occur due to the initial investment C_I. Once the PV system is installed, continuous costs for operation and maintenance c_{OM} incur and the PV installation offers the opportunity to generate revenue by selling electricity to the grid ($R(q_{togrid})$) and to reduce electricity costs by self-consuming electricity from the PV installation ($C(d_{total} - q_{self})$). By assumption, costs and revenues are constant over time, but discounted on a yearly basis t at an interest rate r. We briefly describe the institutional and regulatory framework in Germany and discuss the incentives for PV investments over the years.

3.1. Regulatory framework for residential PV in Germany

The grid feed-in of a residential PV installation is regulated under the EEG, and residential PV owners receive a feed-in tariff, paid for each kilowatt-hour (kWh) of electricity fed into the grid. The feed-in tariff varies depending on the date, size, and type (roof-top or ground-mount) of the installation.

Feed-in tariffs are determined administratively by the government, and the level and the categorization are regularly adjusted for new installations. Residential PV installations with 10 kW or

[4] To fully reflect the potential temporal discrepancy of PV generation and the household's electricity consumption, an (hourly) time index could be introduced (see e.g. Ossenbrink (2017) for a more detailed representation). However, for simplicity and without loss of generality, we refrain from this issue in the following representation.

[5] We focus on the economic rationale in terms of cash flows and do not consider the utility function of the household. One can think of factors that increase the utility beyond the financial aspects, e.g. environmental preferences, and those that have a negative impact, e.g. behavioral biases like inertia or myopia.

smaller have always been eligible to receive the highest possible feed-in tariff. In contrast, larger installations have been subject to some changes in the definition of their support categories over the years. Adjustments of the level of feed-in tariffs are mainly based on the development of PV investment costs which has led to a declining trend over the past years (see figure 1). While the feed-in tariff was about 43 ct/kWh in 2009, this has been reduced to about 12 ct/kWh by 2017. In addition to the feed-in tariff, from 2009 until 2012, the EEG granted an additional remuneration for self-consumption. Although this remuneration was lower than the feed-in tariff, e.g., 25 ct/kWh compared to a feed-in tariff of 43 ct/kWh in 2009, households benefited from self-consumption on top of the savings from reduced electricity consumption costs (Bundesnetzagentur, 2021a).

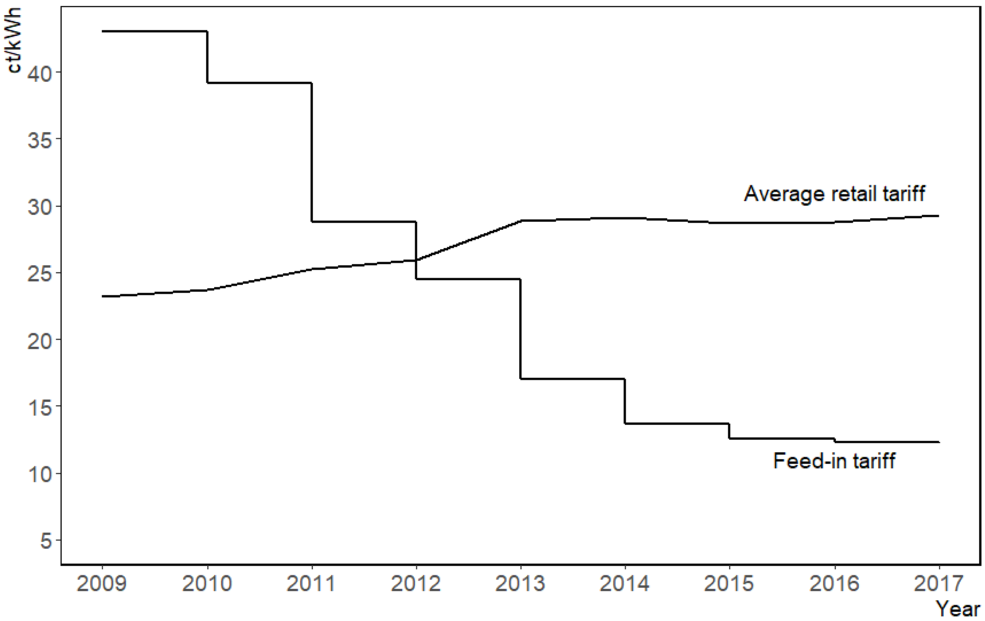

Figure 1: The development of feed-in tariffs for PV installations $<$ 10 kW and average retail tariffs for households in Germany between 2009 and 2017. Own illustration based on data from Bundesnetzagentur (2021a) and BDEW (2021).

3.2. Retail electricity tariffs and the incentive for self-consumption

The value of self-consumption depends on the consumption costs that can be reduced for each kWh of grid consumption substituted with self-generated PV electricity. PV owners can profit from self-consumption because the household's electricity bill in Germany mainly depends on the actual consumption. The retail tariff for grid consumption is nonlinear and consists of a volumetric and a fixed price component, i.e., it constitutes a two-part tariff.

The volumetric price per kWh typically predominates, whereas the fixed component, i.e., the basic price for being served and connected to the network, accounts for a smaller proportion of total retail costs. Furthermore, the retail tariff in Germany comprises of three elements: procurement and sales costs of the retailing firm, network tariffs, and administratively determined taxes, charges, and levies. The latter include, for example, the tax on electricity, the EEG-levy, and the concession fee. In 2017, for instance, these three elements split up into 19 % procurement and sales costs, 26 % network tariffs, and 55 % taxes, charges, and levies (BDEW, 2021). Households do not have to pay the volumetric parts of the network tariff and all taxes, charges, and levies for self-consumption.[6] Following the theory on nonlinear pricing, the fixed price component of the retail tariff should not affect the economic rationale to invest in PV installations. These costs always have to be paid unless the household becomes fully independent and, thus, disconnected from the grid. The volumetric tariff describes the opportunity to purchase electricity from the grid and thus, represents the value of self-consumption.

Furthermore, and in contrast to the feed-in tariff that applies equally for all households across Germany, retail prices vary regionally. While wholesale market prices and taxes, charges, and levies are the same across Germany, the network tariff is the only cost component that systematically differs on a regional level.[7] In particular for residential consumers connected to the low-voltage network, network tariffs are increasingly diverging.[8] The regional variation of distribution network tariffs in Germany is due to the allocation mechanism, a so-called vertical mechanism, by which network operators allocate the network costs to network users (c.f. Jeddi and Sitzmann, 2019). In Germany, the network costs are refinanced by electricity consumers. The allocation is based on the principle that costs incurred in a particular network area are borne by consumers connected to the respective network. Network operators calculate the network tariffs on an annual basis, based on their individual, regulated revenue cap. In practice, this regulatory procedure means that network

[6] Though there were changes regarding the EEG-levy for self-consumption in 2012, residential PV installations with 10 kW or less have always been exempted.

[7] The concession fee can also vary depending on the network area. However, the magnitude is legally fixed, so that the differences are minor compared to the variation in network tariffs.

[8] See e.g. Hinz et al. (2018) and Schlesewsky and Winter (2018) for further investigations.

costs of the current year are decoupled from this year's network tariffs and rather passed on to the network tariffs in later years.

3.3. The economic rationale for investments in PV installations

The profitability of a PV investment hinges on the the value of self-consumption, the feed-in tariff and the interaction of both options. On the one hand, substituting electricity from the grid reduces electricity costs. On the other hand, each kWh used for self-consumption cannot be fed into the grid, i.e., the PV owner does not receive the feed-in tariff. Therefore, it is not only the absolute level of prices and tariffs compared to the PV installation costs that is decisive, but also the relation of the feed-in tariff to the retail electricity price. We apply the regulatory setting in Germany to equation (2). The expected revenue consists of the subsidization of grid feed-in via feed-in tariffs (p^{fit}), self-consumption via a reduction of electricity consumption costs valued at the volumetric tariff (p^{retail}), plus, if applicable, the additional subsidy for self-consumption (p^{self}):

$$NPV = -C_I + \sum_{t=0}^{T} \frac{q_{togrid} \cdot p^{fit} - [(d_{total} - q_{self}) \cdot p^{retail} + q_{self} \cdot p^{self} - c_{OM}]}{(1+r)^t} \quad (3)$$

Equation (3) shows that as soon as the volumetric retail tariff (p^{retail}) rises above the feed-in tariff (p^{fit}), self-consumption becomes financially more profitable compared to grid feed-in.

The feed-in tariff has been continuously decreasing to accommodate the declining costs of PV installations and technological developments. Contrarily, the average retail tariff across Germany has been increasing in most years. Both developments are depicted in figure 1 for the period between 2009 and 2017. Since 2012, the average retail tariff is higher than the feed-in tariff by a constantly increasing margin. Therefore, we expect the investment incentives for residential PV adoption to be increasingly affected by the incentive for self-consumption rather than the feed-in tariff. If this holds, the impact of price signals should have become more relevant since 2012. The abolition of the explicit subsidy for self-consumption in 2012 should have further strengthened the influence of the implicit incentive of the retail tariff.

However, one should keep in mind that self-consumption is attractive only if the household can use the electricity when the sun shines or if a storage opportunity exists. Installation numbers of batteries in households only recently begin to increase as storage is still relatively costly (Figgener et al., 2021). If storage opportunities become economically attractive, the incentive for self-consumption might increase in the upcoming years. Thus, it could become interesting to distinguish between PV systems with and without battery storage.[9]

In principle, the economic incentives of PV adoption apply equally to all households. The feed-in tariff does not vary regionally across Germany, and thus, all else equal, it should have a similar impact on the investment decision. In contrast, the retail tariff varies throughout Germany, and, therefore, the implicit investment incentive from self-consumption can differ between regions. As summarized in section 3.2, the variation is mainly driven by the network tariffs of the distribution grid and our empirical strategy takes advantage of this heterogeneity to investigate the impact of price signals on PV installations in Germany.

4. Empirical strategy

Our objective is to identify whether network tariffs influence investments in PV installations. Therefore, we set up our analysis on postcode-specific panel data for Germany and exploit the regional variance of network tariffs across Germany. Our dependent variable, the number of new PV installations ($Y_{i,t}$) per postcode (i) and year (t), is a count variable, i.e., it follows a non-negative distribution and can only take on integer values. Given the characteristic of the dependent variable and the panel data structure, we employ a Poisson quasi-maximum likelihood estimator with multiple fixed effects (PQMLE) (c.f. Wooldridge, 2010). The consistency of the estimator neither requires that our dependent variable follows a Poisson distribution nor any additional assumptions concerning the distribution of our dependent variable. As part of the estimation procedure, we calculate robust standard errors. By clustering the standard errors at a regional level, we accommodate for arbitrary correlation across clusters. The choice of the PQMLE approach as our preferred estimation method is in line with recent research by Gautier and Jacqmin (2020) and de Freitas (2020), who apply it in a similar setting.

[9] Due to the low number of installed batteries and data availability, we refrain from including batteries in this analysis. Predictive simulations for the development of combined PV and storage systems in Germany can be found, for example, in Kaschub et al. (2016), Fett et al. (2021) and Günther et al. (2021).

The formulation of our preferred estimation model is as follows:

$$Y_{i,t} = exp(\beta \cdot tariff_{i,t-1} + \gamma \cdot X_{i,t} + \phi_t + \mu_i + \theta_i \cdot t) \cdot \epsilon_{i,t} \tag{4}$$

, where $tariff_{i,t-1}$ is our primary explanatory variable, $X_{i,t}$ is a vector of postcode-specific covariates, ϕ_t are year-specific fixed effects, μ_i are postcode-specific fixed effects and θ_i are postcode-specific time trends. $\epsilon_{i,t}$ is an error term.

In our preferred model specification, we lag our primary explanatory variable by one year. Although fully rational households should form an expectation about future electricity costs, in practice, it may be reasonable to assume that households are rather short-sighted and base their expectation on current electricity costs (c.f. Ito, 2014). Since households pay their electricity bill annually and ex-post, there is a time lag of one year between the temporal validity of the network tariff and the cost realization. In addition, some time passes between the investment decision and the actual PV installation, e.g., due to administrative reasons, also justifying the use of the lagged network tariff as the explanatory variable. An advantageous effect of using the time lag is that it helps us to alleviate the strict exogeneity assumption of our primary explanatory variable. The endogeneity concerns arise because, in recent years, network tariffs increase mainly due to network expansion costs which in turn are due to the integration of renewable energy sources, including residential PV installations (c.f. Just and Wetzel, 2020). However, PV adoption in the current year does not affect the network tariffs of the previous year. Therefore, based on our choice of lagged network tariffs as our explanatory variable and because network tariffs reflect historical network costs, we suggest that reverse causality is not a concern in our setting.

We further include a vector of covariates to control for observable heterogeneity of postcode areas. This vector contains the average income and age of the population, the share of detached and semi-detached houses in the building stock, and the number of residential buildings.

The fixed effects approach takes advantage of the panel data structure of our data and allows us to control for unobserved heterogeneity. By applying multiple fixed effects, we can isolate and identify the impact of our primary explanatory variable on the dependent variable based on the within-postcode variance in our data. A random effects model would not be consistent as we expect a correlation between the individual effects and the independent variables.[10] By including year-specific fixed effects, we control for overall developments over time. Examples are declining prices for solar modules or national policy changes, in particular changes in feed-in tariffs. Another aspect covered by these effects is the development of retail price components that do not vary across Germany, such as the EEG-levy or wholesale electricity prices. Postcode-specific fixed effects account for factors that regionally differ between postcode areas but are constant over time, e.g., socioeconomic aspects and solar irradiance.[11] Postcode-specific time trends control for any linear postcode-specific development over time that is not addressed by the nationwide year-specific fixed effects. Examples of such trends include local demographic change or local economic growth.

In addition to the PQMLE, other commonly used models in count data applications are, for example, negative binomial regression models or OLS models with a logarithmized dependent variable. We include these models as robustness checks for our main findings.

To analyze the effect of the nonlinear pricing schedule, we apply the encompassing approach by Davidson and MacKinnon (1993), which can be used to identify a preferable model specification for non-nested models. We specify the encompassing model as an augmented model of (4) and include both alternative explanatory variables, i.e., the volumetric tariff ($tariff_{i,t-1}$) and the average tariff ($\varnothing\text{-}tariff_{i,t-1}$):

$$Y_{i,t} = exp(\beta \cdot tariff_{i,t-1} + \delta \cdot \varnothing\text{-}tariff_{i,t-1} + \gamma \cdot X_{i,t} + \phi_t + \mu_i + \theta_i \cdot t) \cdot \epsilon_{i,t} \quad (5)$$

We want to test our hypothesis that the volumetric tariff impacts PV investments rather than the average tariff. Hence, we expect that as long as the model accounts for the volumetric tariff, the coefficient of the average tariff δ is statistically insignificant, i.e., not influencing the number of PV installations, and we can check this hypothesis with a standard F-test (c.f. Greene, 2003).

[10] A Hausman test rejects the null hypothesis that there is no significant correlation at the significance level of 1 %, which supports the choice of a fixed effects approach.

[11] Generally, solar irradiance is a decisive variable influencing residential PV investments. However, we assume that households do not account for the (relatively small) solar irradiance variation over time. Instead, we expect that households consider it as a spatial component, such as whether one lives in a generally sunnier region. Therefore, we do not include solar irradiance as a covariate in our model, as it is reflected in the postcode-specific fixed effects.

5. Data

For our analysis, we use a unique panel data set at the German postcode level. The panel data set covers 8,148 postcodes (PLZ) for 2009-2017, a total of 72,672 observations. For our dependent variable we rely on data from the Marktstammdatenregister (MaStR) (Bundesnetzagentur, 2021b). For each unit, the MaStR documents the energy carrier, the installed capacity, the postcode, the installation date, and various additional information. In this paper, we focus on PV installations with a size up to 10 kW as this is the typical size installed on residential buildings. Our data consists of 708,555 PV installations commissioned between 2009 and 2017. By aggregating the number of new PV installations per year and postcode, we receive our dependent variable (# *of PV*).

Furthermore, we use detailed data on annual network tariffs on postcode level from ene't, a German data provider for the electricity industry (ene't, 2021). The data contains information on the annual fixed component of network tariffs (*fixed_ tariff*, in Euro/year) and the volumetric component (*tariff*, in ct/kWh). For our investigation of price perception, we use both components to calculate an average tariff (∅-*tariff* in ct/kWh) by assuming a reference load profile of 3,500 kWh annual consumption.

To analyze whether network tariffs had a greater impact on the number of PV installations after 2012, we define two binary dummy variables: One that takes on the value 1 for all years before 2012 ($d_{<2012}$), and one that takes on the value 1 otherwise ($d_{\geq 2012}$).

We further control for the heterogeneity of postcode areas by including socioeconomic drivers of PV expansion that have been identified in the literature described in section 2. We use yearly and postcode-specific data for these socioeconomic covariates from RWI-GEO-GRID, a data set from the Leibniz Institute for Economic Research (RWI) (RWI and Microm, 2020). First, we consider the average purchasing power of households per capita (*income*, in Euro/year). We expect a positive impact of the purchasing power of households on PV expansion as the investment costs of the installation are more likely to be afforded by more affluent people. The variable *age* denotes the average age of inhabitants in a specific postcode area. One would assume that a younger population is more aware of the possibility to invest in PV, thus leading to a negative influence of average age on our dependent variable. For the number of residential buildings (*buildings*), which is closely

Table 1: Descriptive statistics, 2009-2017 (N = 73,329)

Variable	Mean	Median	SD	Min	Max	Source
Dependent variable						
# of PV	9.66	6	11.57	0	184	MaStR
Independent variables						
tariff (ct/kWh)	5.29	5.08	1.04	2.38	9.90	ene't
fixed_tariff (Euro/year)	21.56	18.00	17.72	0	95.00	ene't
∅-tariff (ct/kWh)	5.90	5.65	1.24	2.67	11.55	ene't
income (log of)	9.95	9.95	0.19	9.30	11.01	RWI
housetype (% of 1- and 2-family homes)	58.32	63.64	20.69	0.30	100	RWI
age	43.74	43.58	2.35	35.11	58.48	RWI
buildings (log of)	7.40	7.46	0.92	0.69	9.80	RWI

correlated with the number of inhabitants, we would expect a positive effect on our dependent variable as more buildings in a postcode mean more opportunities for PV investments. Further, we include the share of detached and semi-detached houses in the building stock (*housetype*, in %). Detached and semi-detached houses are well suited for residential PV installations, for example, due to the unity of electricity consumer and investor. Therefore, we would expect a positive impact of the housetype on our dependent variable.

6. Results

We estimate the impact of network tariffs on residential PV installations in Germany within our preferred model specification, described in section 4. Further, we analyze whether the incentives for self-consumption have become more relevant in recent years compared to the early years of PV adoption and how the nonlinear pricing schedule affects PV adoption. Using additional model specifications, we also check the robustness of our results.

We present our main results regarding the impact of network tariffs on PV adoption in table 2. Regression (1) shows our preferred model specification (c.f. equation 4), which estimates the impact of lagged network tariffs on the number of new PV installations, controlling for socioeconomic covariates. Our estimation suggests that network tariffs have a positive and significant impact on the number of PV installations. All else equal, an increase of one eurocent per kWh in network tariffs is estimated to increase the number of PV installations by 5.8 %. The impact of the other covariates is not statistically different from zero. The fixed effects absorb their impact due to their relatively low within-variance, which is depicted in Appendix A.

Table 2: Main results

Model:	(1)	(2)	(3)	(4)
Dependent Variable:	# of PV	# of PV	# of PV	# of PV
tariff_{t-1}	0.0578***			0.0914***
	(0.0061)			(0.0208)
$\text{d}_{<2012} \times \text{tariff}_{t-1}$		0.0112		
		(0.0083)		
$\text{d}_{\geq 2012} \times \text{tariff}_{t-1}$		0.0707***		
		(0.0064)		
$\varnothing\text{-tariff}_{t-1}$			0.0577***	-0.0386*
			(0.0066)	(0.0224)
income (log of)	-0.0334	0.0230	-0.0374	-0.0332
	(0.1497)	(0.1488)	(0.1502)	(0.1495)
housetype	0.0041	0.0050	0.0037	0.0042
	(0.0042)	(0.0042)	(0.0042)	(0.0042)
age	0.0168	0.0184	0.0160	0.0171
	(0.0136)	(0.0136)	(0.0137)	(0.0136)
buildings (log of)	-0.1225	-0.1363	-0.0988	-0.1287
	(0.1688)	(0.1688)	(0.1687)	(0.1689)
Fit statistics				
observations	64,531	64,531	64,531	64,531
AIC	330,230	330,094	330,271	330,225
BIC	476,772	476,644	476,812	476,776
Log-Likelihood	-148,967	-148,898	-148,987	-148,963

Robust standard errors clustered at the postcode level.
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

We further examine whether the incentives for self-consumption have become more relevant in recent years compared to the early years of PV adoption. Therefore, we analyze how the change in the economics of PV investments from 2012 onward has affected the impact of network tariffs on PV installations in Germany (c.f. section 3). We include an interaction term between our binary dummy variables ($d_{<2012}$ and $d_{\geq 2012}$) and the network tariff in regression (2). This estimation allows us to compare the effect of network tariffs before and after 2012. The results suggest that network tariffs did not significantly impact PV adoption before 2012, while they do afterward. We estimate that, since 2012, an increase in network tariffs of one eurocent per kWh increases PV installations by 7.1 %. A Chow test confirms the difference between the estimates of the two time-subsets, revealing significance at the 1 % level. Hence, we can confirm our hypothesis that self-consumption has gained importance since 2012 when rising retail tariffs started to exceed declining feed-in tariffs. We further examine how the different price components of nonlinear tariffs impact PV installations. We make use of the volumetric and the fixed component of network tariffs and test the theoretical expectation that PV adoption should only be affected by the volumetric tariffs. In a first step, we estimate the impact of average instead of the volumetric tariffs in regression (3). This estimation yields similar results compared to our preferred model specification with the volumetric tariffs in regression (1). In a second step, we jointly test the two alternatives in the encompassing model (c.f. equation 5). In regression (4), we include both the volumetric (tariff_{t-1}) and the average tariff ($\varnothing$-tariff_{t-1}). The coefficient of the volumetric tariff is still positive and statistically significant, while the average tariff does not have a statistically significant impact on the number of PV installations. Thus, the encompassing test confirms the theoretical expectation that volumetric tariffs drive PV investments. The results indicate that consumers differentiate between the price components of the two-part tariff, which contributes to the empirical evidence on consumers' perception of nonlinear pricing. Consumers may understand the taxonomy of the two-part tariff and base their investment decision on the volumetric rather than an average tariff. However, given the aggregate nature of our data, this finding should be complemented by further analysis of microeconomic data. In table 3, we provide several robustness checks regarding our model specification and our estimation strategy. In regression (5), we check our assumption that PV adoption is impacted by the lagged network tariff rather than the contemporary one by using the contemporary tariff ($tariff_t$) as our explanatory variable instead of the lagged network tariff ($tariff_{t-1}$). The results indicate a positive effect of the current network tariff on PV adoption. However, the coefficient is smaller compared to the impact of the lagged network tariff in regression (1). Moreover, in regression (5), the values of the two information criteria, AIC and BIC, increase while the value of the log-likelihood decreases compared to regression (1), implying that the explanatory power of our preferred model specification is higher. This finding supports our assumption that households respond to their electricity bill rather than current tariffs and, thus, may have a rather short-sighted perception of prices.

Table 3: Robustness checks

Model:	(5)	(6)	(7)	(8)	(9)
Dependent Variable:	# of PV	# of PV	# of PV	log(# of PV +1)	# of PV
tariff_t	0.0351***				
	(0.0056)				
tariff_{t-1}		0.0725***	0.0540***	0.0478***	0.0550***
		(0.0153)	(0.0047)	(0.0056)	(0.0045)
income (log of)	-0.1770	-1.320**	0.6786***	-0.0810	0.7198***
	(0.1468)	(0.5806)	(0.1241)	(0.1462)	(0.1140)
housetype	0.0152***	0.0286**	0.0017	0.0051	0.0027
	(0.0038)	(0.0144)	(0.0030)	(0.0036)	(0.0028)
age	-0.0043	0.0547	-0.0997***	0.0153	-0.1025***
	(0.0131)	(0.0571)	(0.0076)	(0.0116)	(0.0070)
buildings (log of)	-0.1371	-0.5982	0.1874	0.0796	0.2362*
	(0.1543)	(0.5511)	(0.1379)	(0.1386)	(0.1285)
Fixed effects					
PLZ	Yes+ slope		Yes	Yes + slope	Yes
year	Yes	Yes	Yes	Yes	Yes
NUTS-3		Yes + slope			
Distribution	PQMLE	PQMLE	PQMLE	OLS	Neg. Bin.
Fit statistics					
observations	72,672	3,192	64,531	65,179	64,531
AIC	375,142	32,949	338,674	91,389	330,167
BIC	523,758	37,864	411,999	239,563	403,492
Log-Likelihood	-171,406	-15,664	-161,257	-29,384	-157,003

Robust standard errors clustered at the regional level.
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

We aggregate our data to the next higher regional level (NUTS-3) in regression (6) to check whether our results remain valid at a higher regional aggregation. The estimation suggests that, even under a higher regional aggregation, network tariffs positively and significantly impact PV investments, supporting the results derived from postcode-level data. In regression (7), we estimate our preferred model specification without the postcode-specific time trends. We observe that the positive and significant impact of network tariffs persists. Further, as expected, income has a significantly positive and age a significantly negative impact on the number of new PV installations. Hence, in our preferred model specification, the postcode-specific time trends do indeed capture the assumed postcode-specific demographic change and local economic growth.

Lastly, we apply alternative estimation strategies to determine the impact of network tariffs on the number of PV installations. First, regression (8) assumes a linear relationship, using an OLS regression. To accommodate for the non-negative nature of our count data, we take the log of the dependent variable to which we add one unit due to the presence of zero outcomes. Second, we estimate a negative binomial regression (9). Negative binomial regressions make stronger assumptions regarding the distribution of the dependent variable, which do not fully hold for our data. However, the results can provide a robustness check. Overall, both results confirm the finding of our preferred model specification, that higher network tariffs lead to more PV installations.

7. Conclusion

Within a net purchasing system, investment incentives for residential PV arise from feed-in tariffs and the value of self-consumption. With the latter becoming the dominant economic driver, network tariffs, which constitute a substantial part of the consumption costs, are expected to gain importance. By exploiting the regional heterogeneity of network tariffs, we investigate whether network tariffs encourage to invest in PV systems using a unique panel data set at the German postcode level over the period 2009-2017. We further evaluate how the nonlinear tariff structure impacts residential PV adoption.

We use a Poisson quasi-maximum likelihood estimator with conditional fixed effects and provide additional robustness checks for various distributional assumptions and the regional aggregation level. All else equal, an increase in network tariffs by one eurocent per kWh is estimated to increase PV installations by 5.8 %. Thus, our results indicate that network tariffs impact PV adoption across Germany. We find evidence that the impact of network tariffs has increased over time, supporting our expectation that the economic incentives for self-consumption have become more important in recent years. Furthermore, our analysis of the different price components indicates that the volumetric network tariff drives PV adoption rather than the average price.

For policymakers, our results provide essential insights for upcoming reforms of electricity price components. Our results suggest that households do react to price signals and that prices effectively guide investments. The current incentive for self-consumption is a side effect of the retail tariff design in Germany. Due to taxes, levies and the network tariff design, retail tariffs contain various price components that are not necessarily aligned and, thus, may distort the investment decision of the household in a way that is economically inefficient. If the retail tariff is higher than economically efficient, the incentives for PV investments are distorted. For instance, a feedback effect, as discussed in Jägemann et al. (2013), arises when rising retail tariffs lead to rising residential PV expansion and rising PV expansion, in turn, leads to increasing retail tariffs. Therefore, from an economic point of view, it is essential to create price signals in the least distorting way. In Germany, reform proposals are currently considered for the network tariff system and include a shift from predominantly volumetric network tariffs to a more substantial fixed network tariff. Other proposals aim for a change in the EEG-levy that is currently paid exclusively on a volumetric basis. Consequently, these reforms influence not only household consumption behavior but also investment incentives for PV installations.

The regional variation of price signals may explain at least part of the present heterogeneity of PV installations in Germany. However, as we use fixed effects to control for unobserved heterogeneity between regions, our analysis is limited in this regard. Further analyses could examine the impact of economic factors on the regional heterogeneity across Germany in more detail. Furthermore, declining costs for storage technologies, such as batteries, will further strengthen the case for self-consumption in the residential sector. Therefore, future empirical research could investigate the incentives that drive households to invest in combined PV and storage systems. In a similar vein and in the light of currently increasing adoption rates of electric vehicles and electric heating systems in the residential sector, future empirical analyses could shed light on the impact of price signals on these technologies. Finally, our analysis focuses on the influence of price signals on the initial decision to invest in a PV installation. Another promising field would be to supplement our results with empirical studies on consumption profiles to provide insights into the short-term price sensitivity of households with PV installations.

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Appendix A. Within-variance of the covariates in our sample

Using a fixed effects approach, we exploit the within-region variation of our explanatory variables to identify their impact on our dependent variable. By including time fixed effects, we control for overall developments over time. While this allows us to isolate the effects under investigation, i.e., the effect of network tariffs on PV investments, it prevents us from making statements about the influence of covariates that have little or no within-region variation after controlling for time fixed effects. By regressing the explanatory variables on our fixed effects, we calculate the variation in these variables used to estimate the coefficients in our fixed effects model. The standard deviations of these residuals, calculated for the preferred specification of our model (1) and the specification without the postcode-specific slope (7), are shown in table A.4. The given values may aid in interpreting and classifying the estimated treatment effects of the explanatory variables. For a detailed analysis on the interpretation of fixed effects, refer to Mummolo and Peterson (2018).

Table A.4: Within standard deviation

Model:	(1)	(7)
tariff_{t-1} (ct/kWh)	0.34	0.49
income (log of)	0.02	0.03
housetype (%)	0.63	0.96
age	0.18	0.43
buildings (log of)	0.02	0.02