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Disentangle the price dispersion of residential solar photovoltaic systems: Evidence from Germany

Tobias Kraschewski *, Tim Brauner, Maximilian Heumann, Michael H. Breitner

Leibniz Universität Hannover, Königsworther Platz 1, 30167 Hannover, Germany

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A B S T R A C T

Although Germany has the largest capacity of installed residential photovoltaic (PV) systems in Europe, comprehensive evidence on transparent pricing information remains missing. This study disentangles why PV quote prices are subject to significant dispersion and analyzes which factors influence particularly low- and high-priced systems in Germany. We create a comprehensive cross-sectional dataset of 19 561 PV system quotes from 2011 to 2022 and use regression analyses to investigate the effects of system characteristics, installation scope, and location-related parameters on quoted prices. Our results reveal highly volatile annual price dispersion consistent over 11 years and large price differences despite similar system characteristics. Applying hedonic regression techniques, we reveal spatially fine-resolved price heterogeneity with up to 20 % difference in the German PV market. System characteristics such as battery usage, installation scope, and system capacity have the most significant effect sizes and are instead control variables. More insightful, the installer density shows price-lowering effects, whereas more PV installations per region, higher solar radiation, and higher labor wages cause price-increasing effects. Quantile regression results reveal that installer density promotes the price reduction of high-priced systems more. Scaffolding, AC installation, and elevation are significant price-increasing factors but with small effect sizes. Finally, DC optimizers affect the levels of high-priced systems more than low-priced ones.

1. Introduction

The expansion of residential rooftop photovoltaic (PV) systems represents an important pillar for achieving internationally defined climate targets. With 58.4 GW, Germany has the largest installed PV system capacity in Europe (Federal Statistical Office, 2022). The available potential for this technology is estimated to be about 208 GW for municipalities in Germany (Mainzer et al., 2014). The *German Federal Grid Agency* presented corresponding scenario frameworks for expanding renewable energy sources, which are a guideline for the German grid expansion in the upcoming years. Regarding PV systems, this calls for an additional 17.9 GW each year (Federal Grid Agency, 2022).

Rooftop PV's particular advantage is the installation on sealed surfaces, which are not in spatial competition, a common barrier to expanding renewable energies. Furthermore, solar PV is society's most accepted renewable technology (Cousse, 2021), enabling people to participate directly in the energy transition. Rising electricity prices and debate about Germany's dependence on fossil fuels have increased public interest and strengthened various stakeholders' willingness to actively contribute to sustainable energy transformation. Nevertheless, PV systems are preceded by an economic decision, which represents a common barrier against implementation (Karakaya and Sriwannawit, 2015). A PV system's economic viability depends on the total system cost, feed-in tariff, electricity price, and the electricity yield achieved. In some cases, installing solar PV systems may seem too expensive compared to their economic benefits. Therefore, reducing PV system prices and fostering price transparency are crucial pillars to accelerate the further adoption of rooftop solar systems.

Various studies have examined residential PV prices' dependence on system characteristics, installation scope and location-related factors (Dong and Wiser, 2013; Gillingham et al., 2016; Nemet et al., 2017a,b; O'Shaughnessy et al., 2018). These analyses are mainly based on the *Tracking the Sun (TTS)* report series (Barbose et al., 2021); however, this series is specifically focused on the United States (US), which represents a rapidly growing market that has to date, accumulated an installed capacity of 24.3 GW in the residential sector (Solar Energy Industries Association, 2022). Seel et al. (2014) compared the US PV market using *TTS* data with the German market using price data collected from the market research company *EUPD Research* and found

* Corresponding author.
E-mail addresses: kraschewski@iwi.uni-hannover.de (T. Kraschewski), brauner@iwi.uni-hannover.de (T. Brauner), heumann@iwi.uni-hannover.de (M. Heumann), breitner@iwi.uni-hannover.de (M.H. Breitner).

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significant differences. These may indicate that the results of previous US PV market analyses cannot be fully translated to the German market. The *EUPD Research* data representing the only available and current PV price information for Germany and have also been used in other price analyses (Fraunhofer Institute for Solar Energy Systems, 2022; Altenhöfer-Pflaum and Horbelt, 2017). For data collection, *EUPD Research* surveys a sample of 100 installers and calculates the PV price index, including both the quarterly price data of the system and module prices for PV installations smaller than 30 kW (German Solar Association, 2022). The price data are generic, as they do not include detailed system characteristics, are not geographically resolved, and are not fully available to the public. Although there are other resources through concomitant price measures from early funding programs such as the *100 000 Dächer Programm* from 1999 to 2001 (Oppermann, 2002), these are outdated and no longer publicly available. O'Shaughnessy and Margolis (2018) call for increased price transparency as a crucial determinant of lower quoted PV system prices; however, following for the reasons mentioned, this transparency on detailed price information for rooftop PV systems does not yet exist in Germany. Extensive underlying price data are required to facilitate greater insights, but such information is not readily available to researchers and the public sector, which ultimately inhibits more in-depth analyses in this field.

We address this data scarcity problem by leveraging a web-mining approach to collect quote data from the public domain www.photovoltaikforum.com, which enables users to post their received quotes from PV installers to evaluate them by the community. Then, we conduct comprehensive analyses to shed light on price dispersion and explain the underlying factors that influence PV system pricing in Germany. With this, our study covers both descriptive information and regression analyses. The paper's main contributions are that: (i) we generate a dataset that allows for in-depth PV market price assessments in Germany; (ii) we derive a region-specific price overview and identify spatial price heterogeneity; and (iii) using hedonic regression methods, we can quantify the influence of individual parameters on the system price and investigate the significant variation of these pricing drivers on different price quantiles using quantile regression. Identifying and understanding price parameters from multiple perspectives can facilitate the development of more-effective and fact-based measures for policymakers and can help to anticipate or even influence future price developments for solar PV systems, both from a political and a consumer perspective.

The remainder of this paper is structured as follows. Section 2 summarizes our data collection and processing and provides a descriptive analysis of the dataset. Section 3 presents an overview of the methodological details of the used regression analyses. In Section 4, the regression results are discussed and complement the previous descriptive analysis. We conclude with a summary and implications for different stakeholders in Section 5.

2. Data

We conducted a series of data acquisition and processing steps, summarized in Fig. 1. First, we elaborate on the dataset's origin and the subsequent processing in Section 2.1. Then descriptive characteristics of the data sample are discussed, and hypotheses for the price dispersion and the underlying pricing drivers are derived in Section 2.2.

2.1. Data collection and processing

Following a web-mining approach, the stated quotes on www.photovoltaikforum.com were automatically scraped for a period from January 2011 to December 2022. The data include the quote's date, the total PV system price, location information on postal zip code level, module and inverter characteristics, and other system characteristics. The quoted PV system prices include hardware costs for modules, inverter, wiring, support structure, meters, and soft costs for labor, marketing, permitting, other overhead expenses, and installer profit. The data provide detailed information about the system characteristics and encompass the system size, potential battery storage installations, whether the installer fully installs the system, and whether the quote includes a scaffold for installation, the grid-side AC installation, and module elevation.

The data also include module and inverter manufacturer and model names. After correcting spelling and decimal point errors, we cross-referenced the entries against public module and inverter databases (available at https://www.photovoltaikforum.com/mdb/ and https://www.secondsol.com/en/datasheet/inverter/) to standardize the spelling of module and inverter names and manufacturers. Using manufacturers' datasheets, we incorporated the module's efficiency and the inverter power rating into our data. We used the module's efficiency as a measure of module quality. As module efficiency levels have increased considerably over time, we grouped the modules by years to obtain a normalized efficiency range (0–1) for every year that we classified the respective modules. To identify PV systems with DC optimization, all systems with *Solaredge* inverters were assumed with the equipment of DC optimizers. As there can be a small share of other DC optimization manufacturers on the German market, we risk slightly understating our data's actual share of DC optimization. To account for the hardware cost developments, we calculated the module and inverter price index representing the costs as a function of capacity over time, based on a quote subset with module and inverter prices explicitly listed (cf. Fig. 2). We cross-referenced the module index with wholesale PV market data from https://www.pvxchange.com. We found similar cost trends, despite a slightly higher cost level for our calculated module price index, due to additional profit margins compared to the wholesale market. The calculated cost trends for modules and inverters can be considered similar across systems installed in Germany as they are traded internationally. Further, the module index shows comparable development to the wholesale market.

We cleaned and standardized the quote data by removing systems with missing location information, no detailed system hardware information, or no valid postal zip code, and those not located in Germany. We omitted quotes that were non-residential or with a system size above 30 kW. All pricing information in Euros was inflation-adjusted to 2022 and excluded taxes. We cannot guarantee that the mentioned components and scope of costs are always complete. Unobserved add-ons such as re-roofing, monitoring hardware, rewiring of deprecated electrical installations, or extended warranties may be possible for some quotes.

We complemented socio-economic and demographic characteristics associated with quote years and PV system locations on postal zip code or federal state level. Thus, our dataset includes the income (Seils and Pusch, 2022), population density (Federal Statistical Office Germany, 2021), and wages (Federal Statistical Office Germany, 2019). The installer density was calculated based on location information of installers retrieved from the public domains https://www.photovoltaikforum.com/core/business-directory-company-list/ and https://de.enfsolar.com/directory/installer/Germany. We merged installer locations from both domains and removed duplicates. Then, we calculated the number of installers for each two-digit postal zip code region and related this value to the region's population. Installation data of residential PV systems for Germany were taken from the *Marktstammdatenregister (MaStR)* provided by the *German Federal Grid Agency*. From this register, we retrieved the year of installation, location, and installed capacity and computed the additional installed capacity per year and postal zip code region.

From an initial dataset of 21 828 quotes, the final sample consisted of 19 561 observations that served as the foundation for the subsequent analyses.

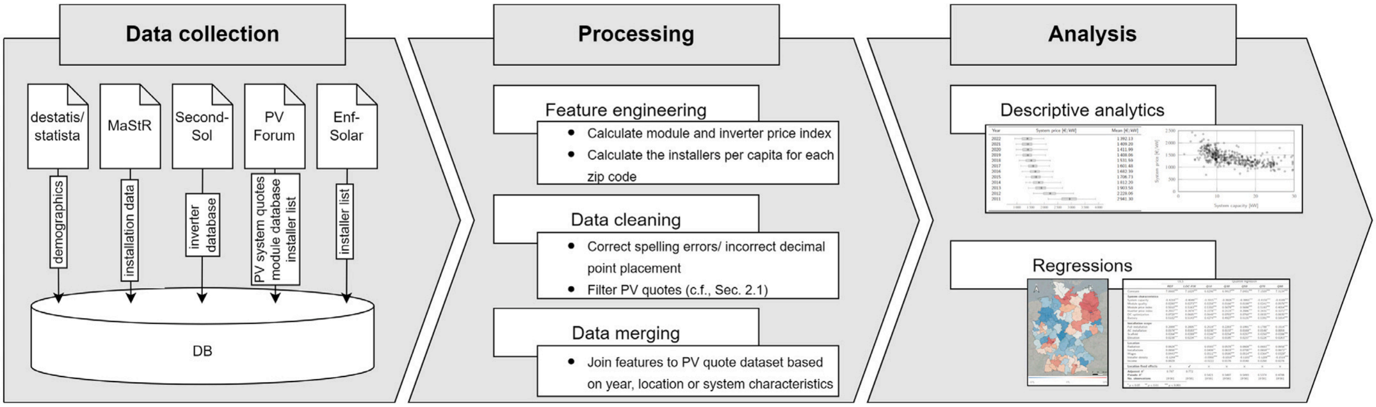


Fig. 1. Data pipeline and subsequent analyses.

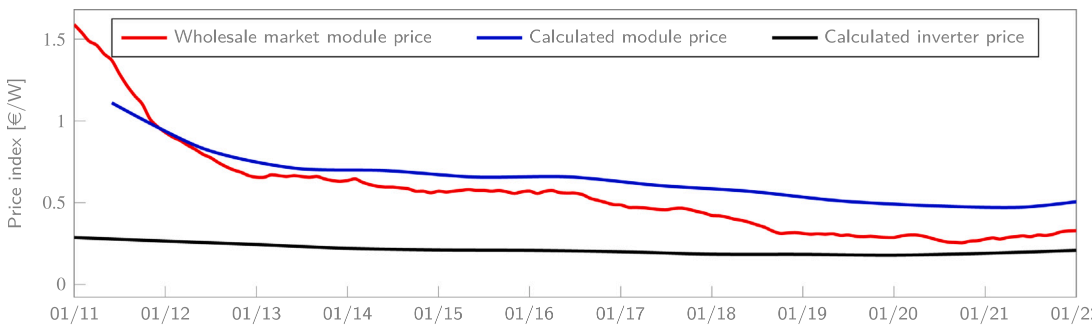


Fig. 2. Photovoltaic module and inverter price index in Germany.

2.2. Descriptive analysis

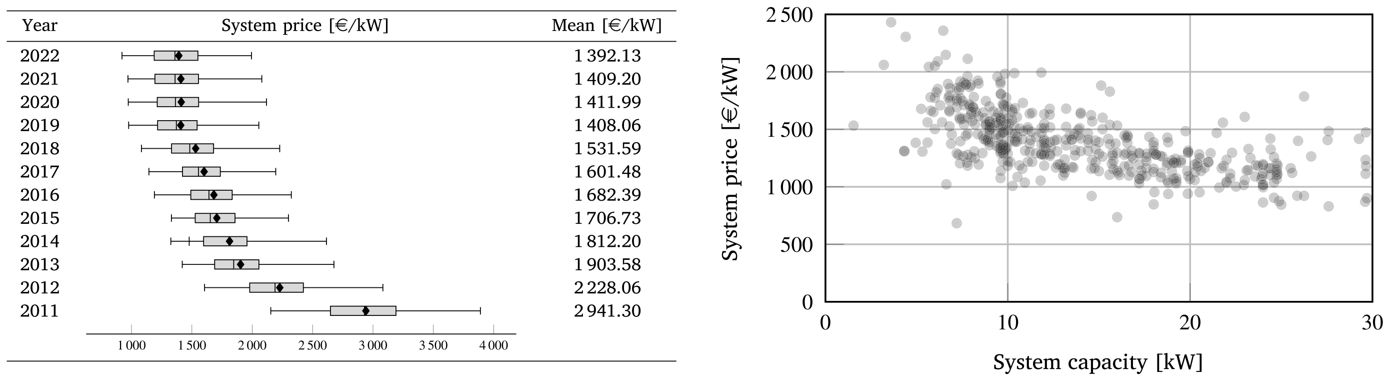
In this section, a descriptive analysis of the residential PV system prices in Germany from January 2011 to December 2022 is conducted to identify the factors affecting their pricing. As depicted in Fig. 3(a), the prices of PV systems have experienced a steep decline over the past decade, largely driven by reductions in hardware and soft costs. The significant decline in PV quote prices from 2011 to 2013 can be attributed to the strong cost reductions of PV modules, as confirmed by Pillai (2015). This trend is also evident in Fig. 2. Still, falling prices have slowed in recent years, reflecting continuous hardware and soft cost reductions. Since 2020, the PV system price development stagnates. One of the main drivers for this stagnation is the increased cost of PV modules due to the increased cost of polysilicon and supply chain disruptions caused by the COVID-19 pandemic (International Energy Agency, 2022). Additionally, growing concerns about the dependence on fossil fuels for energy production and the resulting increase in gas and electricity prices have led to a heightened desire for sustainable energy solutions, which has driven up demand for PV systems. For this reason, hardware costs and PV installation demand are considered explanatory variables for the subsequent detailed price analysis. Moreover, Fig. 3(a) indicates considerable annual variability in PV system pricing, which has largely persisted over time. This variation can reflect differences in PV system characteristics and designs or cost levels across locations and installers. Fig. 3(b) provides the price per system capacity based on quotes for 2022 to eliminate year-dependent factors. Price changes during the year are not included. The mean price of PV installations is 1392.1 €/kW with a large standard deviation of 284.6 €/kW, underscoring the significant price variance.

One explanatory reason for price dispersion is the varying system size, as larger systems benefit from economy of scale effects, which can lead to lower relative system prices (Gillingham et al., 2016; Nemet et al., 2017b; Barbose et al., 2021; German Solar Association, 2022). But even considering similar system sizes, a large price variance is evident in Fig. 3(b). Thus, the system size alone is insufficient to explain the entire price dispersion. Another hypothesis for the variance is that the market may be imperfectly competitive, and similar to other markets, PV pricing is subject to demand- and supply-side factors. For the supply-side, as the number of active installers per region increases, it can be expected that equilibrium PV prices will decline (Gillingham et al., 2016; Nemet et al., 2017b). We further hypothesize that PV price differences derive from heterogeneous labor wages across Germany. Indeed, there is substantial variation in wages, ranging from 21.3 €/h in Saxony-Anhalt to 38.75 €/h in Hamburg for 2020. Similar to Dong and Wiser (2013) and Goodrich et al. (2012), we expect higher wages to increase installation labor costs and thus higher PV system prices. Regarding demand-side influencing parameters and following analyses from Dong and Wiser (2013), the per capita household income might lead to a higher willingness to pay a premium for PV systems. Last, we hypothesize that in regions with high radiation, PV prices will increase because the systems promise a larger yield, and thus a higher value is attributed to the systems.

Previous research from Gillingham et al. (2016) and O'Shaughnessy and Margolis (2018) has highlighted important price-related factors in the US PV market. Moreover, some studies are related to low-priced systems (e.g., Nemet et al. (2017a,b)) and provide insights on certain price quantiles. Using our dataset, comprehensive analyses can be conducted on price-determining factors affecting low- and high-priced PV systems in Germany. In the following, we provide further evidence on price quantile effects and disentangle why PV installation prices vary considerably.

3. Methodology and model specification

We specify two econometric methods to examine PV quote pricing in Germany. First, we define a hedonic pricing model in the sense of Rosen (1974) to investigate factors influencing the price and reveal reasons for regional price dispersion using ordinary least squares (OLS)



(a) (b)

Fig. 3. PV system prices from 2011 to 2022 (a) and PV system prices as a function of system capacity for 2022 (b). PV systems with battery storage or self-installations were left out.

regression. Second, we apply a quantile regression approach to extend our findings to different price quantiles for an in-depth analysis of the quote price distribution.

3.1. Hedonic pricing model

Hedonic price analysis enables the estimation of the implicit price of the considered system characteristics as well as installation- and location-related factors on the observed price. Various studies aim to provide evidence on price dispersion or the factors influencing prices using hedonic regression techniques (Qiu et al., 2017; Hyland et al., 2013; Evangelista et al., 2020; Taruttis and Weber, 2022). Transferred to our study, we regress the PV system price (Y) on several hedonic covariates X, which comprise system characteristics (C), installation scopes (S), and location-related factors (L). Further, we add location fixed effects at two-digit postal zip code level θ_j. The general specification of our hedonic PV quote price model is given in Eq. (1):

$$Y_{ijt} = \alpha + \beta_1 C_{it} + \beta_2 S_i + \beta_3 L_{jt} + \theta_j + \epsilon_{ijt} \tag{1}$$

where Y is the PV system quote price in natural log form, α is the intercept term, β are the variables' associated coefficients, and ϵ is the normally distributed error term. The subscript i denotes the quoted PV system, t denotes the quote's year, and j denotes the respective location. The descriptive statistical summary of all considered determinants in our regression analysis is provided in Table 1. The summary displays minimum, maximum, mean values, and the standard deviation for all the continuous variables. For categorical variables, the number of variables and the reference variable are provided. To verify that the linear regression model is appropriate for our data and the OLS estimator gives the best linear unbiased estimator (BLUE) of the coefficients, we performed multiple tests according to the Gauss–Markov-Theorem. We proved that the residuals are uncorrelated, the residuals' mean is 0, and the errors have equal variance. Additional in-depth data on roof characteristics such as materials, pitch, and height are not included and can account for some of the remaining residuals.

3.2. Quantile regression

Instead of only using OLS regression, which is based on the minimization of the sum of squared error terms and explains the mean of the dependent variable, we also used quantile regression. First introduced by Koenker and Bassett (1978), it is based on the minimization of weighted absolute deviations to estimate conditional quantile functions, which are less sensitive to outliers and facilitate understanding of variables outside the mean of the data. This regression type has become a common statistical method. It involves considering a set of regressions that differ across quantiles of the conditional distribution and is used in multiple economic contexts, including electricity pricing (Maciejowska, 2020), dwelling pricing (Evangelista et al., 2022), or to investigate electricity consumption determinants (Kostakis, 2020). We use quantile regression to reveal quantile effects and highlight how these effects vary across the different levels of the PV price distribution. By calculating coefficient estimates at nine separate quantiles ($\tau = 0.1, \ldots, 0.9$), we can provide a more precise overview of the τth quantile of the price distribution. As in Eq. (1), the τth conditional quantile for $\{y_1, y_2, \ldots, y_n\}$ of Y is assumed to be linearly dependent on X, with the probability density function $F_Y(y) = Prob(Y) \leq y$. The basic quantile regression can be defined as:

$$Q_Y(\tau) = F_Y^{-1}(\tau) = \inf\{y : F_Y(y) \geq \tau\} \tag{2}$$

The distribution is split in proportions above $(1-\tau)$ and below τ. The respective quantile regression estimators $\hat{\beta}_\tau$ can be found through:

$$Q\left(\hat{\beta}_\tau\right) = \sum_{y_{ij} > \hat{\beta}_\tau X_{ij}} \tau \left| y_{ij} - \hat{\beta}_\tau X_{ij} \right| + \sum_{y_{ij} < \hat{\beta}_\tau X_{ij}} (1-\tau) \left| y_{ij} - \hat{\beta}_\tau X_{ij} \right| \tag{3}$$

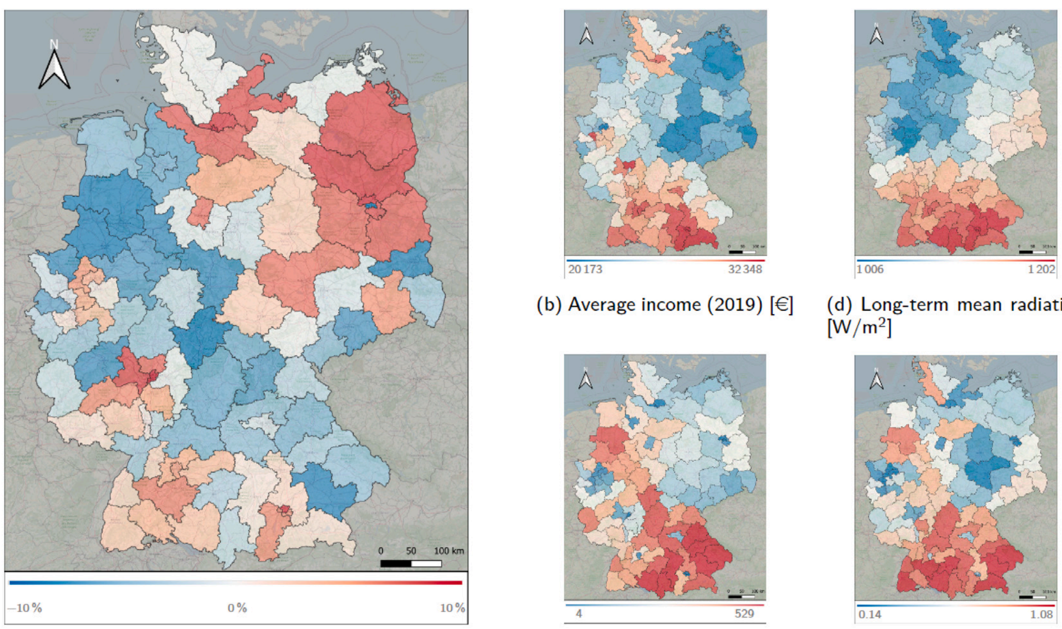
4. Results and discussion

The empirical results of the two OLS and five quantile regressions are summarized in Table 2. The column *REF* defines the reference OLS regression in which no location fixed effects are incorporated. Except for the income variable, all system-, installation-, and location-related variables are significant.

To assess potential spatial price heterogeneity across regions in Germany using OLS regression (Eq. (1)), instead of including location-related variables, we use the two-digit postal zip code to cluster the regions in 95 categorical variables and consider them as fixed effects. This represents a finer spatial resolution compared to the federal state level. In this regression, the location-related variables cannot be included due to multicollinearity. The estimates of the *LOC-FIX* variables differ only marginally from the *REF* model, thus regression results can be considered robust. To visualize the potential spatial price heterogeneity, we depict the resulting fixed effects estimates for the individual postal zip codes in Fig. 4(a) as a heat map. There is a significant price dispersion across Germany (±10% deviating from the average price), where dark blue to blue areas indicate lower price levels and reddish areas are associated with higher price levels. Metropolitan regions such as Hamburg, Frankfurt and Munich show an exceptionally high price level. In this case, it could be hypothesized that high wage and income

Table 1
Summary statistics of variables.

	Definition	Mean	SD	Min	Max	Number of variables	Reference
Dependent variable							
System price	Total PV system price [€]	2 025.21	661.83	550.77	7329.05		
Continuous independent variables							
System capacity	PV system capacity [kW]	9.96	5.49	1.06	29.97		
Module quality	Module quality rating	0.51	0.33	0.0	1.0		
Module price index	Hardware price index [€/W]	0.97	0.36	0.54	1.64		
Inverter price index	Hardware price index [€/W]	0.31	0.08	0.22	0.44		
Wages	Average wages per federal state [€/h]	30.81	2.86	21.30	38.75		
Installer density	PV installers per 10 000 population	0.49	0.19	0.14	1.08		
Radiation	Long-term mean solar radiation [W/m^2]	1 092.44	56.79	1006.05	1202.13		
Installations	Installed capacity [kW] per 10 000 population	145.13	99.54	3.91	528.61		
Income	Per capita income [€]	24 025.76	2350.39	20 109.44	32 347.83		
Categorical independent variables							
Postal zip codes	Two-digit postal zip codes					95	01
Battery	Binary for included battery					2	No
DC optimization	Binary for included DC optimization					2	No
Scaffold	Binary for included scaffold					2	No
Elevation	Binary for included elevation					2	No
AC installation	Binary for included AC installation					2	No
Full installation	Binary for full installation service					2	No



(a)

(b) Average income (2019) [€]

(d) Long-term mean radiation [W/m^2]

(c) Average annual PV capacity growth [kW/a] per 10 000 population

(e) Installers per 10 000 population (2022)

Fig. 4. Spatial PV price heterogeneity in Germany based on OLS estimates for location fixed effects on two-digit postal zip code resolution (a) compared to various location-related factors (b)-(e).

levels in these metropolitan areas lead to higher PV system prices; however, the northeastern and eastern regions in Germany (Brandenburg, Saxony-Anhalt, and Saxony) in Fig. 4(b) prove that high PV system prices prevail even at low income levels. Further, higher PV system prices might be related to higher local installation demand. However, this relationship cannot be confirmed with the addition of Fig. 4(c). Fig. 4(d) indicates that higher solar yields are accessible in the south of Germany due to increased mean solar radiation. It can be hypothesized that system prices will increase in areas with high expected solar yields as these systems are attributed to higher economic viability. But again, no distinct effect on system prices in these regions can be derived. Fig. 4(e) shows the installer density per postal zip code. In conjunction with Fig. 4(a), mixed effects can be found here as well. Areas with a high installer density and the associated market competition show below-average PV system prices in some areas, but the opposing effect can also be identified. Overall, Figs. 4(a) to 4(e) suggest that the price differences cannot be explained straightforwardly by an isolated visual assessment of the factors. Instead, due to overlapping effects, we have to consider these parameters in a differentiated regression analysis to examine their effects on the non-systematic price heterogeneity.

Our *REF* OLS regression measures the impact of 16 factors on PV system price heterogeneity, providing a differentiated investigation of relevant effects. By comparing the *REF* OLS and quantile regression estimates, we quantify variations in the implicit prices along the conditional distribution of PV quote prices. Fig. 5 depicts the regression results for all covariates. The blue line visualizes quantile regression estimates, with the shaded area depicting a 95% confidence interval (CI). The black line represents the OLS estimate of the mean effect; the two dotted lines represent a 95% CI for the respective covariate. Our analysis either refers to the conditional mean or particular conditional quantiles. Higher (lower) priced quotes are located at higher

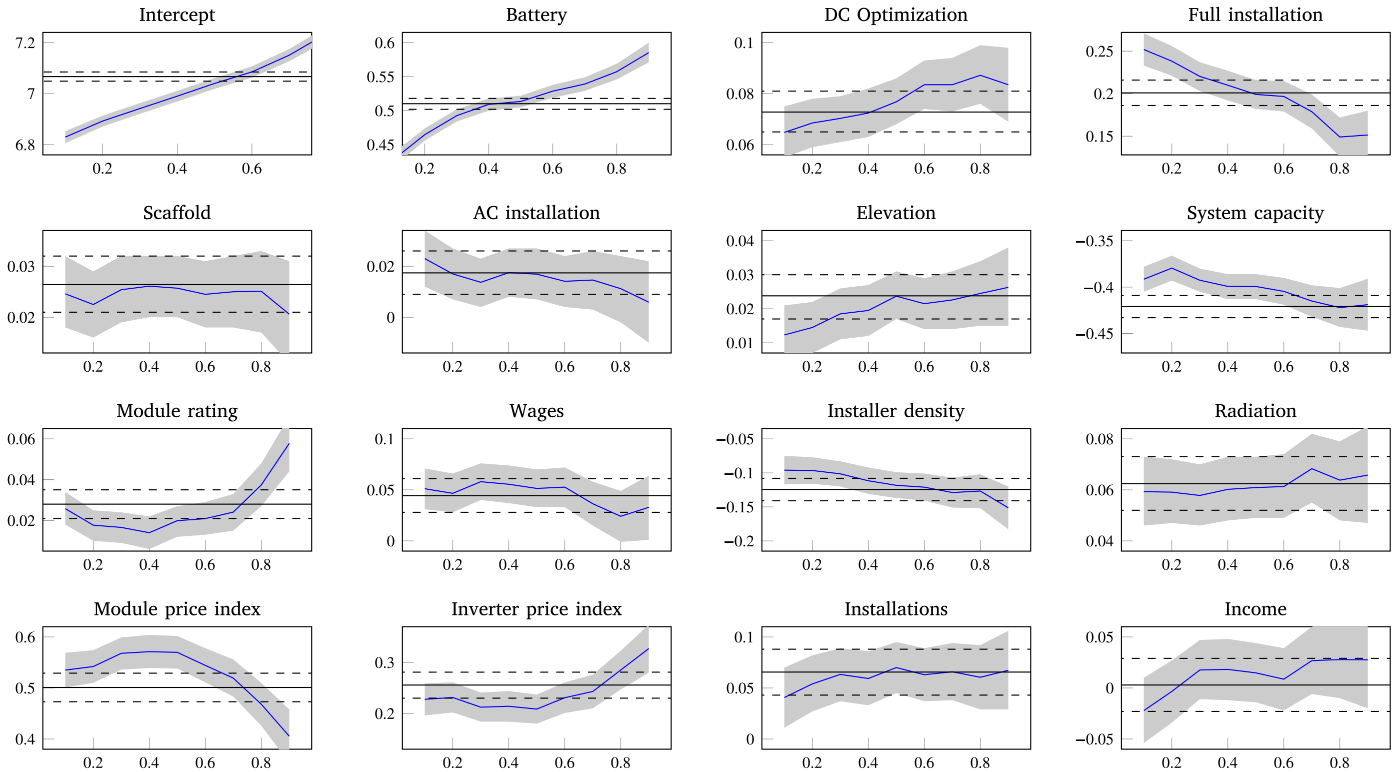


Fig. 5. OLS (REF) estimates (continuous horizontal line) with respective 95% CI as dashed lines, quantile regression estimates (blue line), with respective 95% CI as shaded gray area.

(lower) positions in the conditional PV price distribution based on the covariate value. Regarding the DC optimization, the OLS regression suggests that DC optimization increases PV system prices by 7.28%. The quantile regression estimates indicate an upward trend toward higher-priced PV systems. As the trend clearly crosses the CI of the OLS estimate, using the OLS estimate separately results in overrating the price effects of DC optimization on lower-priced units and underestimating the effects on higher-priced PV systems. Therefore, the installation and associated additional yield from DC optimizer installation should be carefully evaluated. A full domestic installation service without assistance from the homeowner raises the system price by 22.09% and marks one of the most significant variables to cause a price increase in the OLS regression. The quantile regression estimates show the opposite effect compared to the DC optimizer installation. We observe that low-priced PV systems exhibit a notably greater increment in cost when a complete installation service is provided in comparison to high-priced PV systems. This pattern may signify a lower installation effort for higher-priced systems, where components and installation systems used may allow for easier assembly and are, therefore, cheaper to install. In addition, the installation effort with a high share of fixed costs could be less significant for higher-priced systems. Therefore, in contrast with Nemet et al. (2017b), we perceive that German homeowners benefit more from self-installation when purchasing a low-priced system than they do with medium- and high-priced systems. The quantile regression estimates approach the value of the OLS regression at the *Q50*. The requirement for scaffolding during installation, AC installation for grid connection and elevation for flat roofs, are variables with generally low effect and add a premium of only 1.74% to 2.64%. We observe quantile effects consistently within the broad OLS CI for scaffold, AC installations, and elevated mountings. Our results align with those of Nemet et al. (2017a) for the system capacity. Due to economies of scale in installation size, we confirm that greater system capacity leads to significantly lower prices in Germany. Nevertheless, there is substantial variation across quantiles. Lower-priced systems are less sensitive to this covariate than high-priced systems. Compared across all quantiles and respective CIs, high-priced systems can achieve up to 5% more price reduction than low-priced systems. The OLS regression estimates that higher-quality modules are associated with higher system prices by 2.8%, which is consistent with a priori expectations. The quantile regression reveals a U-shape pattern with a decline to the *Q40*, indicating more pronounced effects on lower- and particularly higher-priced systems. Moreover, the decrease at the *Q40* shows that median-priced PV systems are the least affected ones. Our results indicate that local wages increase the PV system price. Looking at the quantile regression, lower-priced systems are relatively less affected by wage costs then more expensive systems, compared to OLS regression. The OLS regression reveal that the installer density has a consistent price-reducing effect up to 12.44%. This finding is consistent with Nemet et al. (2017b), where higher installer density is associated with higher market competition and therefore lower prices. Additionally, the quantile regression shows, that higher-priced systems undergo a greater price reduction than lower-priced ones. The OLS estimate for the radiation parameter is 6.24%, which implies a ceteris paribus higher system price for areas with higher radiation. The quantile estimates are entirely within the CI of the OLS regression. The OLS regression reveals that the number of installations is associated with a price increase of 6.56%. This result confirms that factors related to the demand side, such as the growing demand for PV system installations, are important drivers of PV system prices. Furthermore, the estimated quantile regression coefficients largely fall within the CI of the OLS regression, suggesting that the effect of demand-side factors is consistent across the PV price distribution. Finally, the income variable with a slightly positive effect remains statistically insignificant across all regressions.

5. Conclusions

Through our quote price collection and data processing, we created a dataset consisting of 19 561 PV system quotes and complemented external data sources with information essential to conduct detailed

Table 2
Regression results.

	OLS		Quantile regression				
	REF	*LOC-FIX*	*Q10*	*Q30*	*Q50*	*Q70*	*Q90*
Constant	7.0668***	7.1029***	6.8296***	6.9417***	7.0401***	7.1509***	7.3134***
System characteristics							
System capacity	−0.4210***	−0.4049***	−0.3915***	−0.3926***	−0.3993***	−0.4150***	−0.4189***
Module quality	0.0280***	0.0273***	0.0258***	0.0166***	0.0199***	0.0241***	0.0578***
Module price index	0.5010***	0.5163***	0.5350***	0.5679***	0.5698***	0.5193***	0.4054***
Inverter price index	0.2557***	0.2474***	0.2278***	0.2123***	0.2086***	0.2431***	0.3272***
DC optimization	0.0728***	0.0685***	0.0648***	0.0703***	0.0768***	0.0835***	0.0835***
Battery	0.5102***	0.5143***	0.4274***	0.4927***	0.5135***	0.5391***	0.5854***
Installation scope							
Full installation	0.2009***	0.2005***	0.2519***	0.2203***	0.1991***	0.1788***	0.1514***
AC installation	0.0174***	0.0183***	0.0230***	0.0137**	0.0169**	0.0146*	0.0059
Scaffold	0.0264***	0.0289***	0.0246***	0.0254***	0.0257***	0.0250***	0.0206***
Elevation	0.0238***	0.0234***	0.0123**	0.0185***	0.0237***	0.0226***	0.0263***
Location							
Radiation	0.0624***		0.0593***	0.0578***	0.0609***	0.0683***	0.0658***
Installations	0.0656***		0.0406**	0.0633***	0.0700***	0.0659***	0.0673**
Wages	0.0443***		0.0511***	0.0580***	0.0514***	0.0364**	0.0329*
Installer density	−0.1244***		−0.0960***	−0.1014***	−0.1183***	−0.1289***	−0.1514***
Income	0.0029		−0.0222	0.0176	0.0148	0.0268	0.0276
Adjusted R^2	0.767	0.772					
Pseudo R^2			0.5421	0.5487	0.5493	0.5374	0.4706
No. observations	19 561	19 561	19 561	19 561	19 561	19 561	19 561

*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

analyses. We investigated factors influencing the price of PV systems in Germany using descriptive analysis and hedonic regression. Subsequently, we used quantile regressions to measure the impact of the covariates on different PV price segments. Over the past 11 years, average PV system prices have fallen significantly, but there is a high annual variance in quotes. The analysis revealed significant spatial price differences in Germany, which cannot be explained solely by higher wages or incomes. The conducted regressions helped to shed light on the effects of various location-related variables. Structural policies that support the establishment of installation companies and subsidies for installers can be suitable measures for a further PV quote price reduction. Regarding the economic viability of PV systems, the recent PV quote price trend could inhibit the further expansion. Policymakers should address the mentioned problems with fact-based measures, to which our study can contribute.

As an outlook and further use of our results, we recommend promoting price transparency and making the results and findings accessible to a broader audience through a comprehensive platform. The positive price-reducing effect of such platforms has already been demonstrated (Leibowicz et al., 2019). Potential customers could compare their offer prices spatially and temporally and, if required, adjust the choice of components in their proposed PV installation. The investigated effects of system characteristics on prices could be used to re-evaluate and adjust quotes encompassing DC optimization, high-quality modules, or extensive installation scopes and subsequently lower the overall system cost.

A general commitment to finer resolved, more comprehensive, and continuous data accessibility in the PV price analysis field could support further elaborations on the problems outlined by this and previous studies and facilitate the design of target-oriented and fact-based measures to support the further dissemination of residential PV systems.

CRediT authorship contribution statement

Tobias Kraschewski: Conceptualization, Writing – original draft, Investigation, Methodology, Formal analysis, Data curation, Visualization, Project administration. **Tim Brauner:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Maximilian Heumann:** Writing – review & editing, Methodology, Data curation, Software, Visualization. **Michael H. Breitner:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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