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Residential rent externalities of photovoltaic systems: The relevance of view☆

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ABSTRACT

In a three-dimensional topographic model of Switzerland, we study how the view at photovoltaic (PV) systems affects residential real estate. Our hedonic difference-in-differences regressions provide evidence that the view at a PV system is associated with lower residential rents. We consider different view types to examine amplifiers and attenuators of these negative externalities. Using municipal voting results and data on electric vehicles, we document causal pathways of the effect that align with stated and lived preferences for sustainability. Similar causal pathways of negative externalities are evident through municipalities' solar energy production potential and their local demand elasticities for housing.

1. Introduction

View matters in residential real estate markets (Benson et al., 1998; Bond et al., 2002). Properties with a scenic view across a picturesque lake, a stunning mountain range, an idyllic landscape, a park, or with a view over the city are rented out with a premium. However, the transition towards a more sustainable estate market and more renewable energy supplies changes these views by integrating more photovoltaic (PV) systems into the built environment or rural areas. Consequently, PV installations' visual impact may affect surrounding buildings or residents by becoming a more prominent feature of the city-, town-, and landscape.

In this paper, we assess the impact of having a view at a PV system on residential rental prices. More specifically, we investigate how surrounding residential rents change once a PV installation starts its operation in a neighborhood. In doing so, we distinguish between various view types, which may influence estimation results. For example, we look closer at the external effect of a likely vs. less likely view, the view at single vs. multiple installations, and the view at small vs. large PV systems. Moreover, we analyze if residential rent externalities of PV installations differ for buildings with a scenic view or an internal PV installation. We also explore whether houses and apartments are affected differently by the view at this energy infrastructure. Finally, we investigate the extent to which stated and lived preferences for sustainability in municipalities and a municipality's solar energy production potential drive housing rent externalities of PV installations.

To test these relationships empirically, we introduce a novel approach to model the view at a PV system. By creating a three-dimensional topographical model of our Swiss study areas and employing a ray-tracing procedure, we can categorize the view at PV systems for buildings within an observation circle. We merge this view information with an extensive dataset on rental price observations from real estate listing services (621,010 residential rents). In doing so, we employ a broad sample of various dwelling types, controlling for a battery of housing attributes as well as year- and building-fixed effects in our hedonic difference-in-differences regressions.

Our empirical results demonstrate that the building's view at a PV system (external effect) leads to a depreciation in residential rental

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prices by an average of −1.3% (impaired and unimpaired view), which leads to a reduction in rent of CHF −22.21 per month or CHF −266.48 per year for one average-sized apartment of 80.33 m^2. In comparison, an average-sized PV installation with a potential of 8–10 kilowatt-peak can generate electricity worth CHF 1640 to CHF 2050 in 2021. Furthermore, this negative impact is stronger for the view at multiple PV systems and when seeing a PV installation is more likely. However, the effect is not driven by large and close PV systems. Notably, these installations might benefit the electricity provisions for surrounding tenants. Moreover, the negative impact is stronger for properties with scenic views. Negative rent externalities of PV installations are offset by the internal PV system of the dwelling. By using municipal voting results on the Swiss Energy Act 2017 and the Swiss CO_2 Act in 2021, we show that lower stated preferences for sustainability are a potential driver of negative externality effects of PV installations on residential rents. Similarly, lived preferences for going green, measured by the number and change in registered electric vehicles, allow for the estimation of a similar causal pathway of our main effect. Additionally, a municipality's solar energy production potential yields insights into the dynamics of rent externalities of PV systems across urban (generally higher potential), sub-urban, and rural areas (generally lower potential). Ultimately, we also show that negative rent externalities of PV systems go hand in hand with an elastic demand for housing (approximated by a municipality's vacancy rate in residential housing). Our results also persist in several robustness checks in which we address confounding architectural features, building amenities, timing lags between PV commissioning and actual installation, or unobserved heterogeneity.

This study has important implications for both real estate investors and policymakers. PV systems create negative externalities for surrounding rental buildings, which induce lower rental income for investors. However, this negative impact diminishes if a dwelling has an internal PV system or if it may benefit from large PV installations close by. Hence, it is likely that any negative externalities on tenants diminish if the adoption of PV systems on residential properties benefits not just renters or owners of a house but also residents close by. For policymakers, our study highlights the importance and necessary recognition of neighbors as stakeholders in the approval process of PV systems. For example, Switzerland introduced mandatory PV installations for new buildings with large roofs or fronts (more than 300 m^2) in September 2023. However, this policy fails to address the externalities of PV systems or how electricity is distributed in a neighborhood. In the future, formulating appropriate policies to address the negative externalities is required, and policymakers must account for a PV system's visibility and not just its exposition and, thus, electricity production. In doing so, policymakers can make use of the significant spatial heterogeneity of the effect to reduce the negative impact on the rental housing market. For example, PV adoption policies may focus on areas with higher stated and lived preferences for sustainability, a higher solar production potential (urban areas), or an inelastic demand for housing.

While the impact of seeing large-scale energy infrastructures such as nuclear power plants (Bauer et al., 2017) or wind turbines (Gibbons, 2015; Skenteris et al., 2019) on housing is well documented, there are relatively few studies on how the housing market reacts to the installation of PV systems.[1] In the context of large-scale PV projects, Elmallah et al. (2023) examine the installations' effect on U.S. residential house prices. From a stacked difference-in-differences specification, the authors find that within a radius of half a mile, house prices depreciate by 1.5% compared to homes within 2–4 miles distance. This study also includes view categories such as "average view" and "all other view categories". In contrast, little is known about the link between residential rental prices and the view at PV systems. To the best of our knowledge, we are the first to provide an isolated valuation of the impact of viewing PV systems on residential rents. In this context, we are also overcoming methodological limitations in prior studies by precisely capturing the timing of PV installations, leveraging a very large sample size, and exploiting the geographically as well as politically diverse institutional setting of Switzerland.

The remainder of this study is organized as follows: The next section discusses related literature. Section 3 describes the data, in particular, the topographic data for a three-dimensional model of our study areas in Switzerland and datasets on PV systems and residential rental prices. Section 4 introduces the methodology, more specifically, our novel approach to modeling the view at PV systems. Section 5 presents the results on the external effects of PV systems on residential rents, while Section 6 concludes.

2. Literature review

Related literature mainly focuses on the impact of energy efficiency measures in terms of aggregated energy certificates on housing prices in the owner-occupied real estate as well as the residential rental market. Most of the studies confirm the existence of a green building premium in the housing market. Brounen and Kok (2011) find positive price premiums on houses labeled "green". Kempf and Syz (1994) estimate a total green premium for certified residential dwellings of 2.45% for the Canton of Zurich and 4.91% for the city of Zurich. More granular studies deal with the question of how such certificates affect buildings' energy consumption (Jakob, 2006; Brounen et al., 2012). In the housing market, studies also analyze behavioral aspects of private households when making investment decisions in renewable energy projects (Kempton and Layne, 1994; Greene, 2011; Bull, 2012; Brounen et al., 2013; Wiencke, 2013; Kahn et al., 2014; Ramos et al., 2015).

The location of energy infrastructure is of essential interest to both local communities and policymakers (Clark and Allison, 1999). Therefore, changes in property prices as a consequence of infrastructure policies are a crucial aspect to consider during the respective decision-making process of new energy projects. Hence, research interest in the impact of energy infrastructure on property values has been vibrant. A vast body of literature has focused on the housing price impact of energy infrastructures as this field has gained momentum in the wake of the current challenges of climate change (Fuerst and McAllister, 2011). The meta-analysis of Brinkley and Leach (2019) documents that nowadays, more than half of the empirical studies in this domain are concerned with renewable energy infrastructure, while in the previous century, the major focus was on transmission lines.

A growing body of literature attempts to understand the parameters that drive the public acceptance of renewable energy infrastructure projects (Hoen et al., 2019). Among various parameters, the impact of the energy plant siting on housing values is of particular interest to the local communities and has resulted in many studies. Brinkley and Leach (2019) review 54 studies and conclude that the literature consistently finds positive value impacts from solar rooftops. Cost-savings attributed to low-cost energy projects can be essential drivers of price impacts, according to Fuerst and McAllister (2011). The authors argue that cheap energy provided by a facility or energy efficiency within a property drives attractiveness up, especially for tenants with net rental contracts. Further, increases in rents and asset values in green buildings can be traced to other attributes associated with greater thermal efficiency and sustainability (Eichholtz et al., 2013). These findings are in line with Brändle et al. (2025), who document a low-carbon rent premium (or lower capitalization rates) for low-carbon residential buildings.

Existing studies on rooftop solar installations show consistently statistically significant premiums between 3% and 7% of sale prices (Dastrup et al., 2012; Wen et al., 2018) and between 4% and 6% per watt premium (Hoen et al., 2013) after the installation of a PV system.

[1] PV systems exhibit fundamentally different visual characteristics from those of large-scale energy infrastructure. PV installations are smaller, are roof-mounted, and distributed rather than concentrated in one location, which may generate different types and magnitudes of externalities on housing.

Overall, the findings on the installation of solar rooftops lead to statistically significant property price premiums (D'Alpaos and Moretto, 2019). However, Brinkley and Leach (2019) point out both lessons learned and limitations from previous studies. First, they find that visual attributes, including distance to the energy supply, are important factors that are often not included in quantitative analyses.[2] Second, the authors propose that further studies should be conducted on various types of housing and properties since the prior focus has been largely confined to residential single-family homes. Third, taking pre- and post-tests into account is crucial for a comprehensive understanding of the price impacts of PV systems. Fourth, newer energy plants are less represented in the literature and thus should be more closely examined and compared with older plants. Fifth, they doubt the generalizability of the empirical results from studies due to cultural and regional differences in communities' perceptions, planning processes, and land-use values. This last lesson is particularly important in the Swiss context because of the vibrant differences across cantons. One way to learn about the community's perception could be to look at the voting behavior on energy policies.

3. Data

To run our analysis, we collect data on seven major areas in Switzerland. These study areas comprise the agglomeration areas of Basel, Bern, Geneva, Lucerne, Schaffhausen, and St. Gallen, as well as the whole canton of Zurich. Moreover, our representative study areas cover 185 municipalities that inhabit approximately 30% of the Swiss population (in 2019) while offering various types of city- and landscape features that might influence the rent externalities of PV systems. The selection of study areas is also relatively homogeneous in terms of local income levels, GDP, and sociodemographic characteristics. Like the rest of Switzerland, these study areas are characterized by a high share of renters. On the national level, roughly 60% of the housing stock are rental units.

Moreover, Switzerland's institutional context offers several advantages for our study. First, the Swiss federal institutions offer comprehensive open-source government data that enables precise temporal identification and complete coverage of PV installations. Second, high PV adoption rates across diverse geographic areas provide substantial variation in treatment timing and intensity. Third, the Swiss cultural context combines strong environmental consciousness with aesthetic sensitivities. Fourth, diverse property types, including substantial representation of apartment buildings and mixed-use developments, are common in Swiss urban areas. Fifth, the Swiss setting also provides a valuable policy laboratory for understanding externalities in contexts with strong renewable energy incentives and well-developed planning institutions. Hence, findings for Switzerland may be particularly relevant for other densely populated countries or areas with similar energy transition policies, complementing the predominantly Anglo-Saxon evidence base while offering insights into how institutional contexts shape external effects.

3.1. Photovoltaic systems

We utilize Open Government Data from the Swiss Federal Office of Energy to collect information on the location, output (size), and date of commissioning of PV systems in our Swiss study areas. This database on Elektrizitätsproduktionsanlagen (EPA) contains approximately 110,000 production plants in operation (various types) which are labeled with the Swiss Certificate of Origin of Electricity. In the case of PV installations, all large-scale installations with a capacity of more than 30 kVA are included. Small-scale PV systems (<2 kVA) are covered if a voluntary registration for the certification of origin exists or the installation is subsidized in the form of feed-in tariffs, one-time payments, additional cost financing, or investment contributions. Although the exact number is unknown, the Swiss Federal Office of Energy estimates that its database covers more than 97% of small-scale PV systems due to the high share of subsidization.

As the data from EPA lacks information on the placement of PV systems on buildings, we use a geo data model developed by Meteotest (Sonnendach.ch) to obtain information on the optimal rooftop exposition of individual PV installations. We assume that each PV system is placed in its optimal location on a building according to this model, which assesses the solar potential of all roof surfaces and building fronts in Switzerland.[3] To address potential concerns about the accuracy of our PV placement methodology, we conducted a manual verification using high-resolution satellite imagery for a random sample of installations from our dataset. This robustness check confirmed that our modeling approach, based on Sonnendach.ch's optimal placement recommendations, accurately reflects the actual locations of PV installations. More precisely, 92% of the sampled PV installations are located within the predicted optimal areas of a building's roof.[4]

3.2. 3D topographical data

To create the 3D model of our study areas in Fig. 1, we collect three datasets from the Swiss Federal Office of Topography.[5] Firstly, we utilize the precise digital elevation model from *swissAlti3D*, which describes the surface of Switzerland without vegetation and buildings. This digital terrain model is a raster dataset or an xyz-file in regular grids, where each cell of a grid contains an elevation value. Secondly, we place buildings in this elevation model based on data from *swissBuildings3D 2.0*. This is a vector dataset that represents buildings as 3D models with roof shapes and overhangs. Moreover, each object is described by various attributes (object type, usage, name, etc.). Thirdly, we use the large-scale topographic landscape model from *swissTLM3D* to position natural objects (i.e., trees and forests) and artificial objects (i.e., bridges and towers) in vector form.

[2] Zheng et al. (2023) are among the first to create a visual impact assessment of PV systems while estimating the potential and feasibility of the installations in a built environment (exemplary city in China). However, the authors do not investigate the price impact of such an energy infrastructure in the housing market in this context.

[3] Swiss Energy consultants and installation companies also rely on this model from Meteotest in the process of planning the optimal alignment of a PV system on a roof. Hence, deviations from the model are unlikely and also irrational, as different placements most likely result in a reduction of output.

[4] In this validation check, we randomly selected 75 PV installations from our final estimation sample. Using QGIS, we identified the polygons on roofs that represent optimal PV installation locations according to Sonnendach.ch. In the next step, we conducted a spatial overlay of the optimal location shapefile with official orthophoto imagery provided by the Swiss Federal Office of Topography (which offers superior precision compared to Google satellite imagery and uses consistent coordinate reference systems). We then manually verified whether actual PV installations visible in the satellite imagery corresponded to the optimal locations predicted by Sonnendach.ch. Of the 75 installations examined, 69 (92%) were located within the areas identified as ideal by Sonnendach.ch. The six installations that deviated from optimal placement likely reflect practical constraints such as roof obstructions, structural limitations, or aesthetic preferences not captured in the modeling by Sonnendach.ch. Importantly, we note that satellite images are updated on a rolling basis across different regions over several years, which may introduce some temporal discrepancies between installation dates and image capture dates. However, the high correspondence rate (92%) and the remarkable spatial precision in polygon-imagery overlay strongly support the validity of our PV placement methodology.

[5] The individual databases *swissAlti3D*, *swissBuildings3D 2.0*, and *swissTLM3D* have been continuously updated in previous years. More specifically, while the database on building shapes is updated on a yearly basis, the large-scale topographic landscape model and the elevation model of Switzerland are updated every six years.

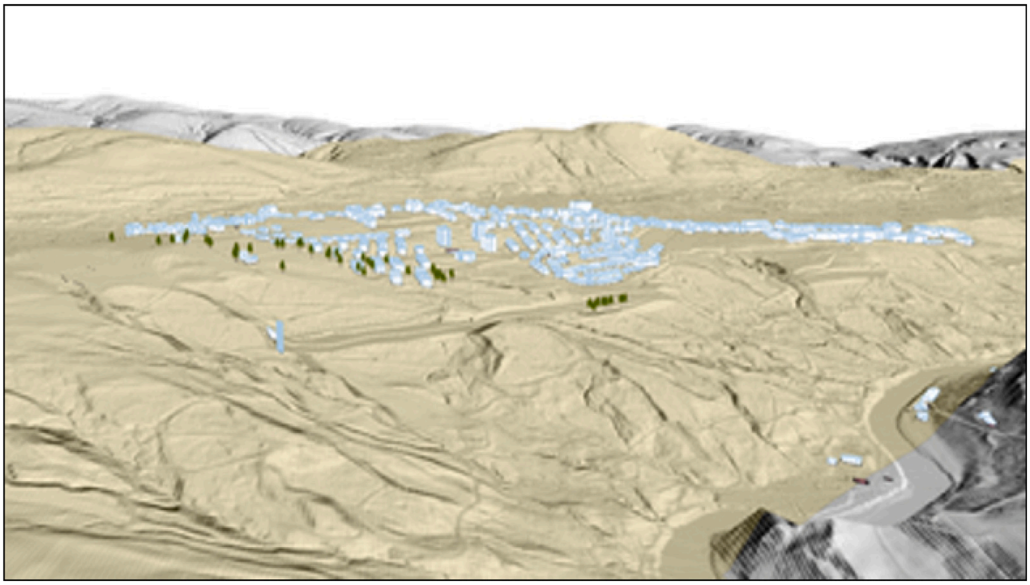


Fig. 1. Topographical data visualization.
This figure visualizes 3D data from the Swiss Federal Office of Topography for a neighborhood in the city of St. Gallen, Switzerland. More precisely, this graph combines a vector dataset of 3D buildings (including shapes and overhangs), a large-scale topographic landscape model of Switzerland (including trees and forests), as well as a precise digital elevation model that describes the surface of Switzerland without vegetation and buildings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Buildings, bridges, and towers have exact so-called polyhedral surfaces in Fig. 1. In contrast, the topography is modeled with an accuracy of 5 m. Trees and forests are positioned without an exact shape description. Therefore, we assume 5 meters of height for trees and forests.

3.3. Residential rents

The extensive dataset on Swiss residential rents is provided by Meta-Sys AG and includes all real estate advertisements in the metropolitan areas of Basel, Bern, Geneva, Lucerne, Schaffhausen, and St. Gallen as well as the entire canton of Zurich from 2004 until 2021.[6] These listings are taken from several online real estate market platforms such as *ImmoScout24.ch* or *Homegate.ch*.[7] In total, the estimation sample includes 621,010 observations of residential rents. All rent observations in this final dataset meet the following criteria: (1) As many real estate listings are published on several platforms, a specific double-filtering process that compares all listings ensures that each observation is unique (duplicates are removed). (2) Each observation includes rental price and surface information. Moreover, observations must include key dwelling characteristics, information on local amenities, and a time stamp.[8] (3) Listings must allow for precise geo-coding and have an exact address. (4) Residential rent observations lie within an observation circle of 500 m for integrated PV systems and 2 km for non-integrated PV systems.

Table 1 shows summary statistics on residential rents and all hedonic characteristics. Monthly average residential rents are CHF 21.27 per m^2 with a range between CHF 9 and CHF 45.70. Besides the dwelling type, our key dwelling characteristics include living space, a first-use dummy, an indicator of scenic view, a dummy for an internal PV system, and the number of rooms. Summary statistics on yearly time dummies in Table 1 also show that our sample is equally distributed across our sample period of 18 years.

3.4. Municipal data

To investigate municipal heterogeneity, we collect specific attributes for all municipalities in our sample from the Swiss Federal Statistical Office's website. These municipal characteristics reflect the population's environmental awareness, the municipality's solar energy production potential, and the demand elasticity of the local residential rental market. Table 2 provides summary statistics of these metrics (equally-weighted municipalities) and forms quartiles based on all municipalities in Switzerland. Table 2 also shows how many of our study areas' rental observations fall into respective municipality quartiles.

First, we are particularly interested in the municipal voting results of two referendums reflecting stated preferences for sustainability.[9] In a first referendum on May 21, 2017, Swiss citizens agreed on the Revised Energy Act that ensures that Switzerland will have secure energy supplies in 2050. This policy includes improving energy efficiency and the promotion of renewable energies such as water, solar, wind, and geothermal power, as well as biomass fuels. Panel A of Table 2 gives more insights into the municipal voting results on the revised Energy Act in 2017. Mean values of municipality quartiles range from 40.1% (Q1) to 69.9% (Q4). In a second referendum on June 13, 2021, the Swiss electorate rejected the Federal Act on the

[6] The time horizon of our dataset on Swiss residential rents spans the COVID-19 pandemic. According to Balemi et al. (2021), who summarize several studies on the housing market during the pandemic, the number of real estate listings dropped as mobility restrictions were hindering the property transaction process. In contrast, Dubler et al. (2021) highlight the special role of the Swiss housing market during the pandemic, which is characterized by rising house prices and stable rents. Due to this special nature, we include the pandemic in our sample.

[7] Advertised offer rents may slightly differ from contractual rents. However, these differences are mostly negligible, in particular for rental prices, as several studies show. In the case of the Swiss residential market, Fleury (2018) shows that asking and contractual rents are identical in most cases, hence, asking rents can be a suitable estimate for the developments in the Swiss real estate market.

[8] A missing number of rooms or a missing dwelling type is set to zero/unknown/unspecified and do not result in dropping an observation.

[9] As outlined by Stutzer and Lalive (2004) as well as Brändle et al. (2025), Swiss citizens are used to expressing their opinions at the poll every annual quarter. Hence, direct democratic decision elements are very common in Switzerland at the municipal, cantonal, and national level.

Table 1
Summary statistics — Residential rents.

	Mean	S.D.	Min	Max
Rent (CHF/m^2/month)	21.266	6.145	9.00	45.70
log(Rent)	3.019	0.271	2.197	3.822
Dwelling type (dummies):				
Unspecified type	0.001	0.033	0	1
Single-family house	0.001	0.027	0	1
Detached house	0.019	0.183	0	1
Semi-detached house	0.003	0.050	0	1
Townhouse (corner)	0.001	0.032	0	1
Townhouse (single-family)	0.004	0.062	0	1
Apartment	0.842	0.364	0	1
Attic	0.028	0.165	0	1
Maisonette	0.043	0.204	0	1
Loft	0.012	0.109	0	1
Penthouse	0.040	0.196	0	1
Studio	0.006	0.078	0	1
Dwelling characteristics:				
Living space (m^2)	80.327	34.379	6	663
log(living space)	4.294	0.442	1.792	6.497
First use (dummy)	0.087	0.282	0	1
Scenic view (dummy)	0.281	0.449	0	1
Internal PV system	0.009	0.094	0	1
Rooms (dummies):				
Unknown	0.019	0.138	0	1
1	0.111	0.314	0	1
2	0.223	0.416	0	1
3	0.347	0.476	0	1
4	0.227	0.419	0	1
5	0.057	0.231	0	1
6	0.012	0.108	0	1
7 and more	0.005	0.070	0	1
Years (dummies):				
2004	0.028	0.164	0	1
2005	0.044	0.205	0	1
2006	0.051	0.221	0	1
2007	0.057	0.231	0	1
2008	0.055	0.228	0	1
2009	0.058	0.233	0	1
2010	0.059	0.236	0	1
2011	0.056	0.230	0	1
2012	0.063	0.243	0	1
2013	0.055	0.227	0	1
2014	0.059	0.236	0	1
2015	0.056	0.229	0	1
2016	0.060	0.238	0	1
2017	0.064	0.245	0	1
2018	0.058	0.233	0	1
2019	0.058	0.235	0	1
2020	0.063	0.243	0	1
2021	0.058	0.233	0	1

This table shows descriptive statistics for the dataset on Swiss residential rents. The mean, standard deviation (S.D.), minimum, and maximum values are listed. Residential rents in this table are asking rents from online real estate listings, comprising 621,010 observations. Furthermore, each observation can be precisely located in Switzerland.

Reduction of Greenhouse Gas Emissions (CO_2 Act), which aims to curb the nation's greenhouse gas emissions even further by 2030. Panel B of Table 2 again lists summary statistics on this referendum and shows that the CO_2 Act in 2021 was only accepted in the upper quartile of municipalities.

Second, we collect data on the number and change in registered electronic vehicles in each municipality from 2015 to 2021. This information allows us to proxy for the population's lived preferences for sustainability. Panel C of Table 2 indicates that, on average, 3.5 electric cars were registered in Swiss municipalities as of 2015. This low average number is driven by the low number of electric vehicles in the first three quartiles of municipalities. However, in the top quartile of municipalities, the number of registered electric cars increases significantly and ranges between 4 and 445. Panel D summarizes the substantial change (increase) in registered electric vehicles from 2015 to 2021.

Third, we also gather data on each municipality's solar energy production potential. This metric summarizes the potential energy production if all suitable roofs and facades in a municipality were equipped with PV systems while considering local climate conditions and geographic locations. Hence, solar energy production potential is positively correlated with urban density. The solar energy production potential is on average 30.7 gigawatt-hour per year, with a maximum of 1130 gigawatt-hour per year.

Lastly, we obtain detailed statistics on the vacancy rate in the local housing market from 2006 until 2021 to proxy for the demand elasticity of housing in each municipality. Panel F of Table 2 shows very low vacancy rates overall, with an average of 1.3%. The highest vacancy rate in Q4 is 6.8%, whereas in 534 out of the 2,136 municipalities, (almost) no vacant space is available.

4. Methodology

4.1. View modeling

To investigate the externalities of PV systems on residential rents, we use a method called "ray tracing" to model the visibility of all PV installations from each building that lies within a pre-defined buffer thereof. This four-step approach is illustrated in Fig. 2.

Firstly, the ray tracing method draws a circle around a specific PV system. Neighboring buildings are identified if they intersect the circle. If no dwelling intersects the circle, a circle with a larger diameter is drawn. Secondly, the shapes of identified buildings are used to draw a cone. The PV system is invisible for objects that lie within a cone as the view is blocked by the identified buildings. These dwellings are removed from this iteration process in a third step. Lastly, this procedure is repeated until the observation circle reaches the pre-defined cut-off distance of the PV system.[10]

Consequently, in this paper, we do not model a view as a precise statement that a PV system can be seen from a specific building window. Instead, our view modeling approach states whether a PV installation can be seen from a specific building floor. In doing so, our classification or view modeling approach distinguishes dwellings with a partial view and buildings with a full/unimpaired view at the PV system. Most dwellings in our dataset have a partial view at an installation as, in many instances, only direct neighbors are able to see a PV system in full.[11] Therefore, we count the number of intersections a building has with different cones (partially seeing score). The further away a building is from a PV system, the higher this score can be, and it is more likely that the installations can only be seen in part from such buildings. For this reason, based on the identification of direct neighbors and the partially seeing score, we further distinguish buildings that are relatively likely or unlikely to have a (partial) view at the PV system.

Most importantly, the ray tracing method is applied to a 3D topographical model (Section 3.2). This setting enables for the classification of views at a PV for buildings as a whole and individual floors. The ray tracing method often eliminates lower floors of a building, whereas higher floors are more likely to have a view at the PV system.

Fig. 3 illustrates the 3D view modeling in a neighborhood of St. Gallen, Switzerland. The PV system is represented by a white dot in the center of the image. Buildings colored in green have (at least in part) a view at this specific PV system. Buildings (or parts of a dwelling) colored in yellow, red, gray, or black cannot see the PV system, as their view might be blocked by buildings, trees, or other objects.

[10] A non-integrated PV system with an assumed size of 100*100*10 m (length, width, height) has an observation circle with a radius of 2 km. An integrated PV system, which is placed on the most efficient location on a roof, has a cut-off distance of 500 m within a city and 1 km outside city borders.

[11] Notably, in the case of direct neighbors, a tree also suffices to reduce a full view at a PV system to a partial view at a given installation.

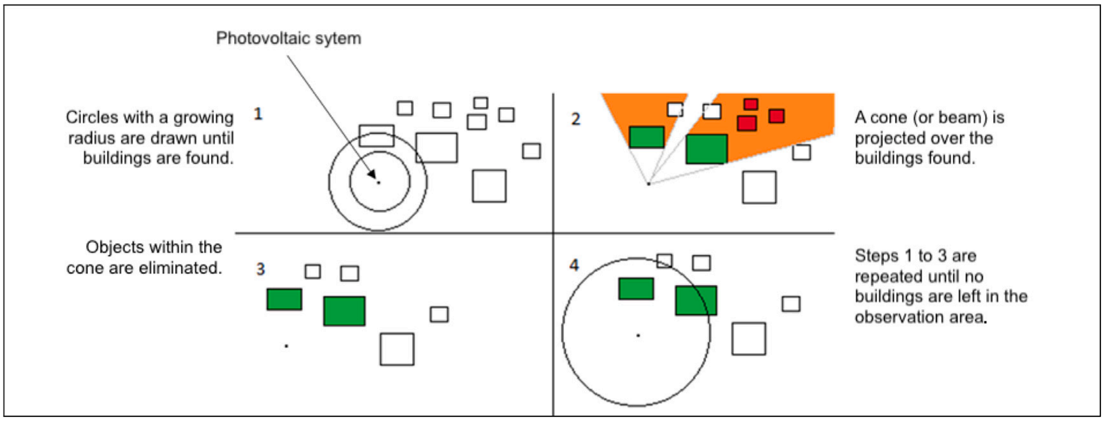


Fig. 2. View modeling – Ray tracing method.
This figure illustrates the process of modeling view at PV systems by the ray tracing procedure. This method includes four steps which are recursively applied in circles with increasing diameters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

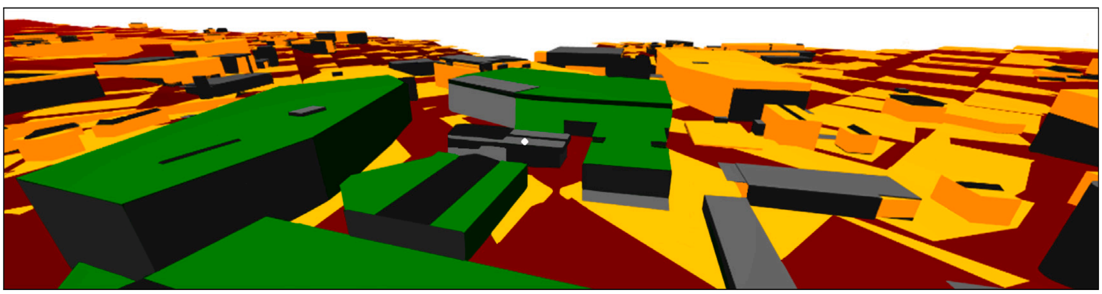


Fig. 3. View modeling — 3D view at a specific PV system.
This figure illustrates the view at a PV system (white dot) in an exemplary neighborhood in the city of St. Gallen, Switzerland. View at PV systems is based on the ray tracing method. Neighboring buildings (or sections of a dwelling) with a view at the installation are colored in shades of green. Neighboring buildings (or sections of a dwelling) without a view at the PV system are colored orange, yellow, gray, or black. Red areas indicate public land used for roads or sidewalks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

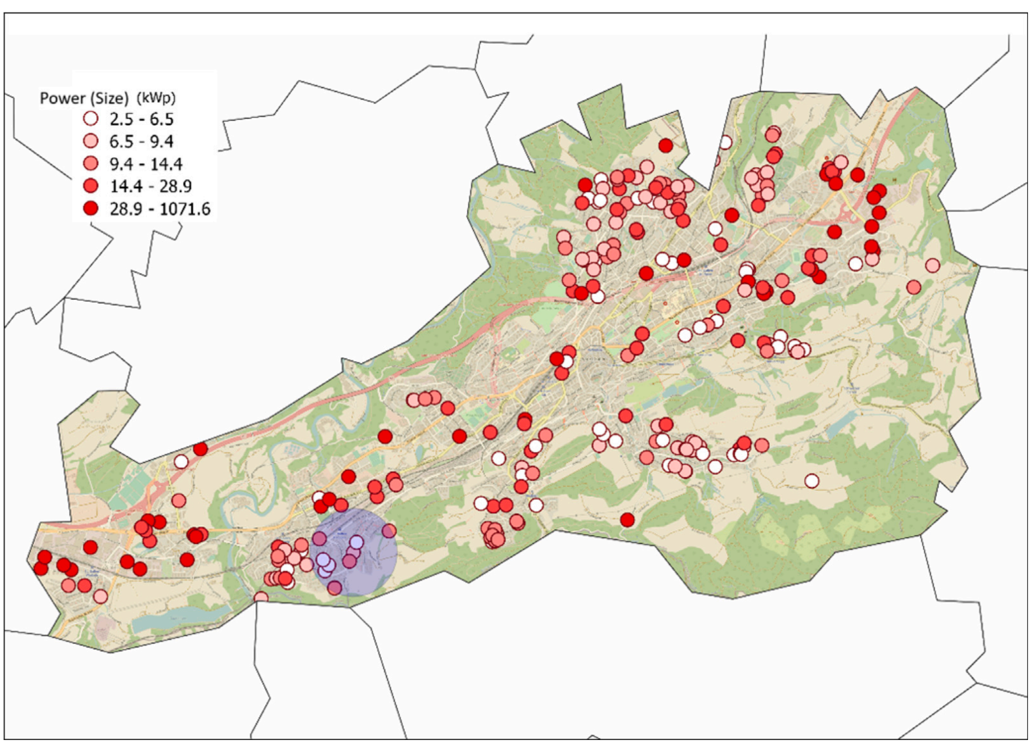


Fig. 4. Mapping PV systems of different size.
This figure plots the location of PV systems in the city of St. Gallen, Switzerland in December 2021. The size of each installation is indicated by varying shades of red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary statistics — Municipality characteristics.

	Swiss municipalities					Study areas:	
	Obs.	Mean	S.D.	Min	Max	Obs. No View	Obs. View
Panel A: Revised Energy Act 2017 — Yes-votes in %							
All	2,244	54.351	11.628	16.071	86.414	254,982	364,909
Q1	561	40.100	5.562	16.071	46.357	11,047	14,349
Q2	561	49.820	2.100	46.362	53.488	31,409	43,639
Q3	561	57.613	2.573	53.502	62.626	45,602	53,231
Q4	561	69.870	4.859	62.658	86.614	166,923	253,690
Panel B: CO_2 Act 2021 — Yes-votes in %							
All	2,176	40.301	10.234	8.108	77.5	244,232	365,705
Q1	544	27.843	5.062	8.108	33.489	1,593	2,044
Q2	544	36.722	1.725	33.492	39.700	9,838	12,032
Q3	544	42.977	2.007	39.704	46.472	24,800	41,849
Q4	544	53.660	5.711	46.472	77.500	219,001	309,780
Panel C: Registered electric vehicles — Number (#) in 2015							
All	2,169	3.472	14.533	0	445	255,332	365,705
Q1	804	0	0	0	0	530	513
Q2	433	1	0	1	1	1,110	679
Q3	447	2.423	0.495	2	3	7,828	9,625
Q4	485	12.400	28.974	4	445	245,764	354,888
Panel D: Registered electric vehicles — Change from 2015–2021							
All	2,169	29.661	80.046	−160	2,628	255,232	365,705
Q1	574	2.153	6.996	−160	5	380	1,995
Q2	532	9.338	2.290	6	13	1,061	996
Q3	534	20.875	4.930	14	30	7,671	11,566
Q4	522	89.611	146.823	31	2,628	246,120	351,148
Panel E: Solar energy production potential (roofs and facades) in gigawatt-hours							
All	2,147	30.681	47.399	0.510	1,130.27	255,061	365,355
Q1	538	5.602	2.107	0.510	9.260	636	657
Q2	536	13.326	2.654	9.280	18.630	4,967	6,616
Q3	537	26.430	5.025	18.68	36.53	17,273	22,577
Q4	536	77.469	76.351	36.540	1,130.27	232,185	335,505
Panel F: Housing vacancy rate — Average share in % from 2006–2021							
All	2,136	1.306	0.964	0	6.809	255,061	365,355
Q1	534	0.361	0.169	0	0.633	113,709	147,855
Q2	534	0.860	0.136	0.633	1.095	89,254	145,840
Q3	535	1.376	0.174	1.096	1.712	25,118	39,879
Q4	533	2.628	0.893	1.713	6.809	26,980	31,781

This table shows descriptive statistics for Swiss municipality characteristics. The number of observations, mean, standard deviation (S.D.), and minimum and maximum values at the municipality level are listed for all municipalities in Switzerland. The number of overall municipalities varies due to data limitations and the fusions of municipalities at different points in time. For our study areas, comprising 185 municipalities, the number of observations with and without a view at PV systems is listed for each municipality quartile.

Fig. 4 indicates that multiple PV systems can be found in most areas.[12] As a consequence, several installations of different types (integrated vs. non-integrated) and sizes may be seen from a building. These multiple relations are summarized and aggregated. For this purpose, we calculate two additional scores: one for identifying large and close PV systems, and another for the overall number of PV installations visible from any one building in our dataset.

4.2. Treatment groups

To define treated observations for our difference-in-differences model (see Section 4.3), we take the date of commissioning of each PV system as the treatment date. To get a better understanding of this treatment while modeling the view at PV systems, we zoom into the area of the blue circle in Fig. 4 (bottom left from center) to obtain Fig. 5.

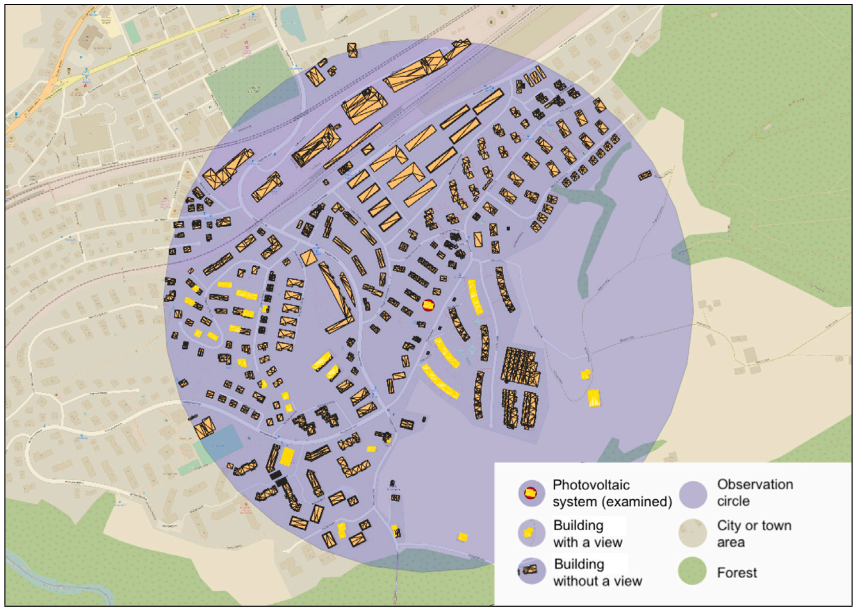
In Panel A of Fig. 5, an observation circle with a cut-off distance of 500 m is drawn around a specific PV system that has just started its operation. According to the ray tracing method, several buildings (colored in yellow) are likely to have a view at the new PV system. More specifically, as this particular PV installation is oriented southwesterly on a pitched roof, only buildings in the southwest may have a view at the installation. On the one hand, some neighboring buildings do not have a view as the dwelling with the PV system is surrounded by trees, which block the view. On the other hand, higher buildings in the south have a partial view. Panel B exclusively considers buildings and floors with an unimpaired view at a PV system. Red shading illustrates higher-up floors with a view.

As the number of rental price observations in buildings with an unimpaired view at a PV system is strongly reduced in Panel B, we opt to consider all buildings that have a view (impaired and unimpaired) at a PV installation as treated. Non-treated dwellings are buildings without a view at a PV system after its date of commissioning, that lie also within its observation circle. To compute the potential treatment effects of seeing a PV system on residential rents, geo-referenced rental price observations have to be mapped for buildings in the observation circle to identify treatment and control groups for our difference-in-differences setting. Fig. 6 visualizes the matching of residential rents with buildings and floors that have a view at a specific PV system. While spatially matching geo-referenced rental prices (from listings data) with buildings' dimensions, the coordinates of these two different data sources are often not identical. We allow for a distance of up to 10 m from the shape of a 3D building for a successful merge. If several buildings are found, the closest dwelling is selected.

Table 3 summarizes how many residential rent observations have a specific type of view at a PV system. In the definition of our treatment

12 To graphically depict PV systems in our model of Switzerland, EPA coordinates have to strictly overlap with polygons of Swiss buildings. Consequently, all other mappings are omitted.

Panel A: Impaired and Unimpaired View within Observation Circle



Panel B: Unimpaired View within Observation Circle

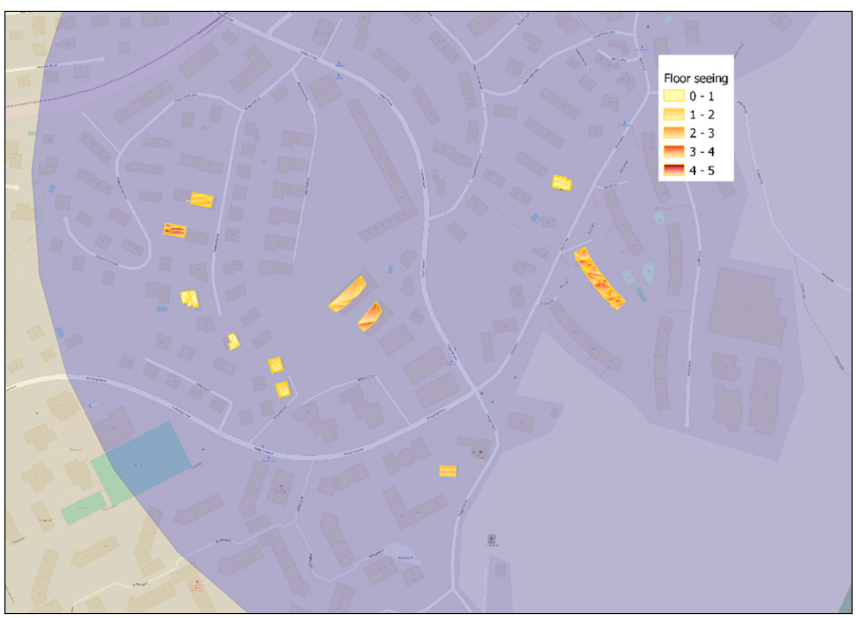


Fig. 5. Buildings with a view at a specific PV installation.
This figure illustrates buildings with a view at a specific PV system in an exemplary neighborhood in St. Gallen, Switzerland. More specifically, Panel A shows buildings with a view (at least partially) at a specific PV system within a 500 m observation circle. Panel B shows buildings with an unimpaired view at the PV installation. Red roofs illustrate higher-up floors that have a full view at the PV system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

groups, we are able to distinguish likely vs. unlikely view, view at a single vs. multiple PV systems, view at a small vs. large and close PV installation, view at a PV system from buildings with vs. without their own PV installation, view at a PV system from buildings with vs. without scenic view, and view at a PV installation from apartment types vs. house types. In the latter case, the apartment types include rental dwellings like attics, maisonettes, lofts, penthouses, studios, or regular apartments, whereas the house types include single-family homes, detached houses, semi-detached houses, or townhouses.

4.3. *Econometric modeling*

Our econometric model aims to measure the rental price effects of viewing PV systems for apartments and houses. To do so, we specify

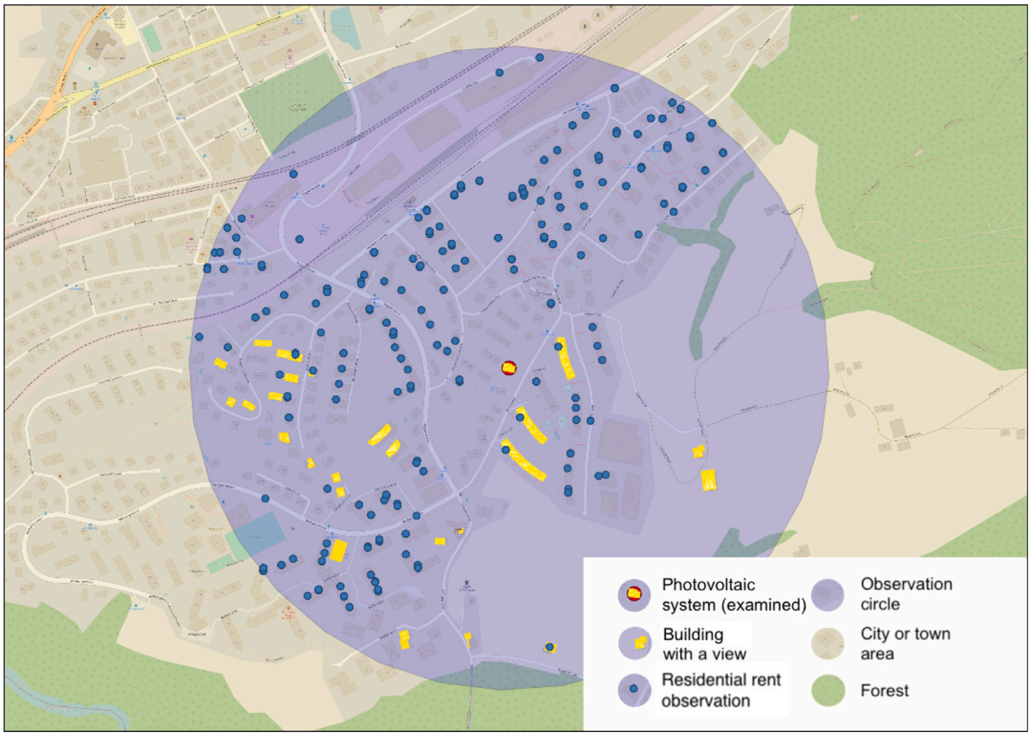


Fig. 6. Residential rents and buildings with a view at a specific PV installation.
This figure visualizes merging residential rent data with buildings or floors that have a view at a specific PV system. Residential rents are depicted by blue dots, while buildings with a view are colored in yellow. Only rental price observations within the observation circle are considered. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Residential rent observations with a view at PV systems.

	Mean	S.D.	Min	Max
View at a PV system	0.589	0.492	0	1
Likely view at a PV system	0.157	0.364	0	1
Unlikely view at a PV system	0.432	0.495	0	1
View at a single PV system	0.103	0.304	0	1
View at multiple PV system	0.486	0.500	0	1
View at a PV system w/o own PV	0.584	0.493	0	1
View at a PV system with own PV	0.005	0.073	0	1
View at small PV system	0.535	0.499	0	1
View at large and close PV system	0.054	0.226	0	1
View at a PV system w/o scenic view	0.419	0.513	0	1
View at a PV system with scenic view	0.170	0.376	0	1
View at a PV system from all apartment types	0.574	0.491	0	1
View at a PV system from all house types	0.015	0.124	0	1

This table shows descriptive statistics for the average share of all residential rent observations with a certain view type on PV systems. The mean, standard deviation (S.D.), and minimum and maximum values are listed. All variables that summarize the view are binary indicators. The number of observations amounts to 621,010.

the following staggered difference-in-differences model, which includes a full set of hedonic characteristics as well as time and building fixed effects[13]:

$$ln(r_{ibt}) = \beta X_{it} + \gamma PV_{it} + \eta_b + \lambda_t + \epsilon_{ibt}, \quad (1)$$

where, the dependent variable, $ln\, r_{ibt}$, corresponds to the natural logarithm of residential rents. The main explanatory variable, PV_{it}, is a binary indicator that equals one if a dwelling has a view at a PV system (i.e., after its installation). X_{it} comprises a set of hedonic attributes, such as the dwelling type (apartment, attic, detached house, etc.), the number of rooms (categorical), first use (newly built or fully renovated object), scenic view, and the living space (see summary statistics in Table 1 of the Appendix for the scaling of the control variables). Fixed-effects at the level of individual years, t, and individual buildings, b, are denoted by λ_t and η_b, respectively. The error term is given by ϵ_{ibt}. Standard errors are clustered at the level of individual buildings.

Following the inference procedure of Callaway and Sant'Anna (2021), we estimate Eq. (1) with multiple time periods and variations in treatment timing. More specifically, our difference-in-differences model is centered around heterogeneous treatments of varying dates of commissioning of multiple PV systems. Coefficient γ on PV_{it} measures the average treatment effect on the treated (ATET) in this staggered treatment adoption, which relies on limited treatment anticipation. Most importantly, our estimation needs to meet the assumption that conditional parallel trends exist based on a never-treated control group

[13] Usually, a PV installation is combined with a heating pump or a hybrid heating system. Heating systems are internal energy infrastructures that might additionally affect the impact of PV systems on residential rents (see, e.g., Kijo-Kleczkowska et al. (2022)). Notably, such effects (if any) are captured by the building fixed effects, which effectively control for differences in structural characteristics of buildings, such as the installed heating system (if time-invariant).

Table 4
External effects of PV systems on residential rents — Baseline.

	Residential rents
View at a PV system	−0.013*** (0.002)
Dwelling type (base category: unspecified type):	
Single-family house	0.024* (0.014)
Detached house	−0.010 (0.006)
Semi-detached house	0.010 (0.012)
Townhouse (corner)	−0.001 (0.014)
Townhouse (single-family)	0.007 (0.010)
Apartment	−0.010** (0.006)
Attic	0.142*** (0.006)
Maisonette	0.013** (0.006)
Loft	0.054*** (0.008)
Penthouse	0.023*** (0.006)
Studio	−0.069*** (0.010)
Dwelling characteristics:	
log(living space)	−0.388*** (0.005)
First use	0.067*** (0.002)
Scenic view	0.020*** (0.001)
Rooms (base category: unknown):	
1	−0.115*** (0.004)
2	−0.026*** (0.003)
3	0.019*** (0.002)
4	0.055*** (0.003)
5	0.099*** (0.003)
6	0.174*** (0.006)
7 and more	0.244*** (0.009)
Constant	4.582*** (0.022)
Year fixed effects	18
Building fixed effects	57,969
Observations	621,010
Adjusted within R^2	0.352

This table lists the results of the staggered difference-in-differences regression for the estimation of the external effects of PV systems on residential rents. View at a PV system is defined as any view (i.e., partially impaired and unimpaired). The dependent variable is the natural logarithm of residential rents. Cluster-robust standard errors (at the building level) are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% level.

(covariates are of minor importance in our model). To verify the validity of this assumption, we employ standard parallel trend tests in all re-estimations of Eq. (1) as well as a comprehensive conditional pre-trend analysis. Furthermore, we compute cohort-specific biennially disaggregated ATETs to explore effect heterogeneity across treatment cohorts and time periods.

Furthermore, we highlight the importance of building fixed effects in our estimation. As our data on Swiss residential rents does not represent a balanced panel dataset, the inclusion of building fixed effects in model of Eq. (1) allows a more robust estimation similar to repeat cross-section data.[14] Moreover, the two-way fixed effects difference-in-differences modeling approach provides a means to address potential concerns about omitted variable bias, which could be reflected in any variable that correlates with both view at a PV system and residential rents but is not included as a regressor in our model.

5. Empirical results

5.1. Baseline effects of viewing PV systems

Regression results of estimating Eq. (1) are listed in Table 4. As outlined in Section 4.1, we classify each building characterized by an impaired or unimpaired view at the PV system as treated. Hence, a dwelling is classified as viewing even if only a small part of the building provides a view at the infrastructure.

The estimates in Table 4 show that scenic views significantly matter in the residential rental market, and so does the view at a PV system. The model, according to Eq. (1), indicates the presence of negative externalities for rental dwellings with a view at a PV system. This rental price penalty for dwellings with a view at a PV system lowers rents by −1.3% on average and is statistically significant at all common statistical significance levels. In terms of economic significance, this effect translates into a decrease in rent of CHF −22.21 per month or CHF −266.48 per year for one average-sized apartment of 80.33 m^2 in a building that gets a view at a neighboring PV system after its installation. In comparison, an average-sized PV installation with a potential of 8–10 kilowatt-peak can generate electricity worth CHF 1,640 to CHF 2,050 per year (based on an average electricity price of CHF 0.205 per kilowatt-hour in 2021). Based on the Swiss electricity mix, this average PV installation saves 4.56 tons of CO2, which are priced at CHF 437.76 in 2021 (Swiss Federal Ministry for the Environment, 2024).[15] Hence, as PV installations can often be seen from multiple apartments simultaneously, the decrease in rental income when having a view at a PV system is substantial compared to electricity production and carbon reductions.

Fig. 7 depicts the disaggregated biennial ATET in the context of residential rents. These results are based on our staggered difference-in-differences regression with building and time-fixed effects, illustrating the treatment effect heterogeneity by cohort and across time in comparison to never-treated rental price observations. Figure A.1 in the Appendix shows a more granular graph of the estimated ATET with re-estimations cohort by cohort.

Furthermore, a parallel-trends test yields an F-statistic of 1.08 with a corresponding p-value of 0.3541. Hence, the null hypothesis that treatment effects in all pre-treatment periods are zero cannot be rejected at a conventional significance level. To provide further evidence, we examine the evolution of rental outcomes for ever-treated properties prior to PV installations versus never-treated properties. Using 2011, the year in which the number of observations by treatment category is approximately equal, as the base year. Table A.2 in the Appendix reveals that while there are some statistically significant differences in the early years of our estimation sample, these differences are positively signed and systematically diminish as we approach later years. Specifically, the differentials between ever-treated properties pre-treatment and never-treated properties decrease from 1.8 percentage points in 2004 to near-zero by 2013 (0.0 percentage points), suggesting convergence in pre-treatment trends. Figure A.2 in the Appendix visually confirms this pattern, with Panel A showing the evolution of (pre-treatment) rental outcomes is largely in tandem for both groups throughout the observation period. Panel B shows that differentials have a positive sign in earlier years, followed by erratic swings around zero (accompanied by inflated standard errors) in later years. The small pre-treatment differentials observed in earlier years likely reflect differences in neighborhood development patterns or market timing, rather than violations of the identifying assumption, as the trends converge in subsequent periods.

As the optimal location of PV systems on pitched roofs is generally directed to the South, critics might argue that the negative external effect of PV systems on residential rents in Table 4 is driven by apartments facing North, which are usually sold or rented out at a lower price. This discount is not the driving mechanism behind our main finding, because a view to the North is already priced in before the treatment date.

Moreover, critics may say that the negative externality of a PV system on rents appears disproportionately large. However, compared to the externalities associated with other architectural amenities, the

[14] In our estimation sample, the average number of rent observations in a building is 11, the minimum is 1 and the maximum amounts to 592 over our sample period of 18 years.

[15] In 2021, the one kilowatt-hour produced by a PV system generates 42 grams of CO2 on average in contrast to an average emission of 99 grams of CO2 in the Swiss electricity mix. One ton of CO2 emissions is priced at CHF 96 according to the Swiss CO2 Levy.

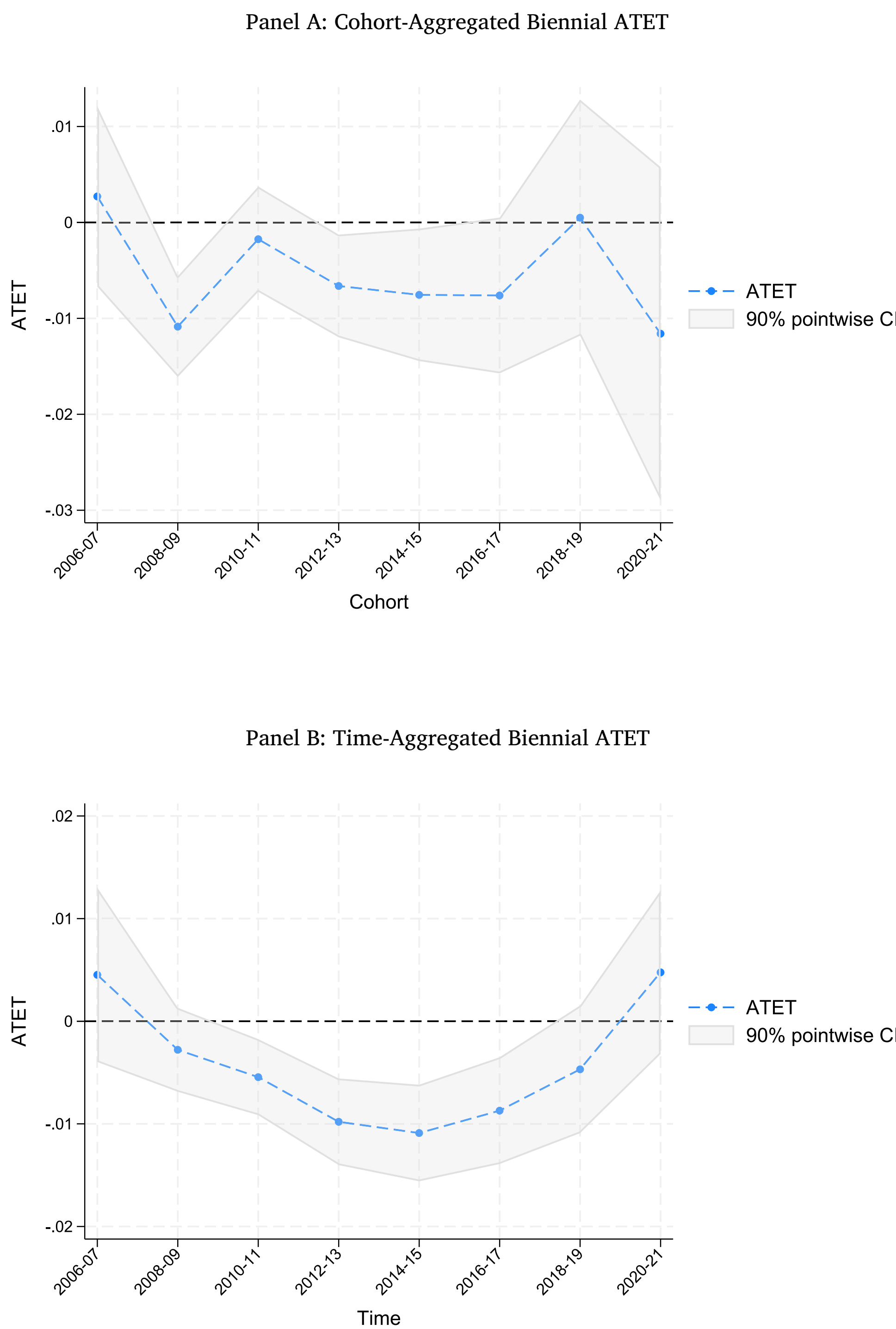


Fig. 7. Biennial ATET plots.
This figure illustrates biennial ATET plots from the staggered difference-in-differences regression to capture the external effects of PV systems on residential rents. View at a PV system is defined as an impaired and unimpaired view. Panel A is aggregated by cohort while Panel B is aggregated over time. Never-treated observations serve as the control group in both panels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

effect we document is of plausible magnitude and falls within the range of documented visual effects in housing markets, as two related studies demonstrate. First, Ahlfeldt and Holman (2018) compare properties outside a conservation area with unobstructed views onto the conservation area (characterized by positive architectural amenities) to adjacent properties that do not have a view. The authors' view boundary discontinuity design yields an estimated price increase of 3% for properties with a view at the conservation area. Secondly, Koster et al. (2016) estimate the impact of historic amenities on house prices using a semiparametric regression-discontinuity approach. The authors find that the effect of external view of historic amenities amounts to 3.5% of the house price.

Table 5
External effect of PV systems on residential rents — View types.

	Residential rents
Panel A: Likely vs. less likely	
Likely view at a PV system	−0.015*** (0.003)
Less likely view at a PV system	−0.012*** (0.002)
Panel B: Single vs. multiple	
View at single PV system	−0.010*** (0.003)
View at multiple PV systems	−0.013*** (0.002)
Panel C: HTE — Buildings with vs. w/o own PV system	
View at a PV system w/o own PV	−0.013*** (0.002)
View at a PV system with own PV *Δ*	0.067** (0.028)
Panel D: HTE — Small vs. large and close	
View at a small PV system	−0.014*** (0.002)
View at a large and close PV system *Δ*	0.017*** (0.005)
Panel E: HTE — Buildings with vs. w/o scenic view	
View at a PV system w/o scenic view	−0.011*** (0.002)
View at a PV system with scenic view *Δ*	−0.008*** (0.001)
Panel F: HTE — Apartment types vs. house types	
View at a PV system from apartment	−0.013*** (0.002)
View at a PV system from house *Δ*	−0.003 (0.004)
Year fixed effects	18
Building fixed effects	57,969
Observations	621,010

This table lists the results of various staggered difference-in-differences regressions for the estimation of the external effects of PV systems on residential rents. The view at PV systems is defined in multiple ways (Panels A-F). The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors (at the building level) are reported in parentheses. The adjusted within R^2 for all regressions reported is approximately 0.35. HTE is short for heterogeneous treatment effects, and *Δ* denotes a differential. *** and ** denote statistical significance at the 1 % and 5% level.

5.2. *Effects of different types of view at PV systems*

Table 5 lists the results of re-estimations of several variants of our difference-in-differences model according to Eq. (1).[16] More specifically, in contrast to the baseline estimation in Panel A, the results in Panels B to G consider different types of views at PV systems to gain a nuanced understanding of the heterogeneity of PV systems' negative externalities across different contexts.

Likely vs. less likely view at a PV: In Panel A, we split buildings, respectively, residential rent observations into two groups according to the likelihood of having an actual view at the PV system (based on the partially seeing score). The first group considers residential rent observations in buildings likely to have a view at a PV. More precisely, this group includes buildings with an unimpaired view and buildings in the bottom quartile of the distribution of buildings with partial intersections. Hence, among dwellings with a potential partial view at PVs, this quartile is most likely to have a view at them. This is because the buildings in the first 25% are closer to the installation, have few intersections with cones in the ray tracing procedure, and therefore, might provide a comparably good view at a PV system. The second group comprises buildings in the second, third, and fourth quartiles of the distribution of dwellings with a partial view, which are less likely to have a view at a PV system. This 75% of dwellings with a potential partial view are located farther away from PV installations, have many intersections with ray tracing cones, and thus, might not provide a good view at an installation. The difference-in-differences regression results in Panel B underscore the baseline estimation on the relationship between residential rents and the view at PV systems. A likely and less likely view yields a similar negative coefficient at the 1% level of statistical significance.

View at a single vs. multiple PVs: As depicted in Fig. 4. PV systems may be located in the center of the built environment. Therefore, seeing multiple installations might also influence residential rents to a higher degree. To explore this relationship, we re-estimate the difference-in-differences model, differentiating between the view at single and multiple installations. The corresponding results are listed in Panel B of Table 5. An estimated coefficient of −1.0% for a view at a single PV and an estimated coefficient of −1.3% for a view at multiple PVs indicate that the view at multiple PV installations does matter somewhat more for rental properties.

Buildings with vs. without own PV: In Panel C of Table 5, we test whether the rent externalities of having a view at a PV installation change for dwellings that house their own PV system. Residents of buildings with an installed PV system might be more positively inclined towards seeing other PV systems, as they benefit from their rental dwelling's own PV installation through a self-consumption agreement with their landlord (Article 17 of the Swiss Energy Law).[17] Similar to previous estimations, there is a statistically significant negative effect of −1.3% for residential rents in buildings without their own PV system and with a view at another installation. An internal PV system on a building that actually has a view at another PV installation compensates for this negative externality by far (a positive rental price differential of 6.7% creates an overall rental premium of 5.4% (−1.3% + 6.7%-points) compared to buildings without a view). Hence, rental housing in buildings with their own PV installations still documents higher rents when exposed to a view at a PV system.

View at a small vs. large and close PV: Additionally, we adapt our difference-in-differences setting to consider whether a PV installation is

[16] To present these estimations in a concise way, estimated coefficients of controls are henceforth not listed. However, we comment on anomalies where applicable.

[17] In Switzerland, the owner of a rental dwelling equipped with an internal PV system can force new tenants to enter a self-consumption arrangement (ZEV or Zusammenschluss für Eigenverbrauch). Within such an arrangement, a landlord sells electricity produced by the internal PV system to tenants at a below-market rate (at a maximum of 80% of the current market rate). Moreover, landlords may sell excess energy to the grid (typically, feed-in tariffs are lower than the price per kilowatt-hour paid by renters in the self-consumption arrangements).

large and close in Panel D of Table 5. Corresponding results show that residential rents are significantly impacted by small PV installations in a negative way, whereas large and close PV systems show an overall positive differential (the difference outweighs the negative effect of view at a small PV installation by three percentage points and creates an overall external effect close to zero). This finding might be explained by preferences for a clear structural accent in a neighborhood rather than smaller (scattered) installations for aesthetic reasons. Furthermore, it is possible that renters directly benefit from the electricity production of large installations nearby. Tenants can do so in two ways. First, tenants can join a self-consumption agreement across multiple properties (with neighboring landlords) if the PV system is large enough and can provide sufficient electricity of the required quality at all times. Secondly, if the large PV system is installed and operated by the local electricity provider, the municipality's population often has the opportunity to purchase individual panels and benefit from their electricity production.[18]

Buildings with vs. without scenic view: Negative residential rent externalities of PV systems might affect properties with a scenic view more strongly. We verify this hypothesis in Panel E of Table 5. An overall negative effect of −1.1% is documented for rental observations without a scenic view. This negative impact increases by an additional −0.8%-points (differential) if a scenic view exists (overall effect −1.9%).

Apartment types vs. house types: As outlined in Section 4.2, we also form two categories for dwelling types — apartment types vs. house types. This simple differentiation in Panel F of Table 5 allows an exploration of residential rent externalities of PV systems across two major dwelling types. PV systems have a negative impact of −1.3% on rents for all apartment types. A comparison with our baseline estimation in Panel A shows that these two coefficients are almost identical. This suggests that the overall effect across our sample is driven by rental apartments, where the small category of rental houses, for which we do not document a statistically significant differential, is not a driver of the main effect.

5.3. Preferences for sustainability and the view at PV systems

Stated preferences: To examine a potential causal pathway, we link the location of residential rent observations with the stated political attitude in a respective municipality, similar to Brändle et al. (2025). More precisely, we split residential rent observations based on quartiles of the share of yes-votes in two referendums (from the lowest to the highest support in a municipality) to investigate heterogeneous treatment effects for municipalities with different stated political attitudes towards sustainability. The two political referendums are the Revised Energy Act in 2017 in Panel A and the Federal Act on the Reduction of Greenhouse Gas Emissions (CO_2 Act) in Panel B. Panel A in Table 6 shows that the negative effect of having a view at PV systems stems from the lowest quartile, i.e., municipalities with the lowest preference for sustainability-related policies (highest proportions of rejecters of the Revised Energy Act in 2017). Compared to the higher quartiles (differentials), with higher environmental awareness and acceptance of this referendum, the acceptance of PV installations reduces the negative impact on residential rents step-by-step and turns it slightly positive in the fourth quartile. Moreover, these differentials are confirmed by the results in Panel B, which are derived from the CO_2 Act in 2021. The negative coefficient of −5.5% in the first quartile of the yes-vote distribution is highly statistically significant and of similar magnitude.

Table 6
External effect of PV systems on residential rents – Stated preferences.

	Residential rents
Panel A: HTE — Revised Energy Act 2017	
View at a PV system (yes-votes (Q1))	−0.059*** (0.004)
View at a PV system (yes-votes (Q2): Δ)	0.016*** (0.004)
View at a PV system (yes-votes (Q3): Δ)	0.028*** (0.004)
View at a PV system (yes-votes (Q4): Δ)	0.064*** (0.004)
Year fixed effects	18
Building fixed effects	57,725
Observations	619,890
Panel B: HTE — CO_2 Act 2021	
View at a PV system (yes-votes (Q1))	−0.055*** (0.008)
View at a PV system (yes-votes (Q2): Δ)	0.000 (0.009)
View at a PV system (yes-votes (Q3): Δ)	0.015* (0.009)
View at a PV system (yes-votes (Q4): Δ)	0.051*** (0.008)
Year fixed effects	18
Building fixed effects	57,964
Observations	620,937

This table lists the results of staggered difference-in-differences regressions for estimating the causal pathway of the external effect of a PV system on residential rents. Quartiles at the municipality level are based on voting results of the Revised Energy Act in 2017 and the CO_2 Act in 2021 (yes-votes), reflecting the municipal population's stated preferences for sustainability. HTE is short for heterogeneous treatment effects, and Δ denotes a differential with the respective first quartile. The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors at the building level are reported in parentheses. The number of observations in Panels A and B differs due to the fusion of municipalities between 2017 and 2021. The adjusted within R^2 for all regressions is approximately 0.35. *** and * denote statistical significance at the 1% and 10% level.

Again, differentials for upper quartiles diminish the effect step-by-step. We estimate a differential of 5.1%-points in the top quartile (with the highest rate of electoral support for the CO_2 Act) in comparison to the lowest quartile.

Lived preferences: We also utilize data on the number and change of electric vehicles in a municipality to measure varying degrees of peoples' lived preferences for going green in a similar quartile split. Table 7 presents results on how lived preferences for sustainability go hand in hand with rent externalities of PV systems. Panel A shows a causal pathway of the main effect. The strongest driver of the effects is the lowest quartile of observations in municipalities with the smallest absolute number of registered electric vehicles (lowest lived preferences for going green). In this first quartile, the estimated rental price effect of having a view at a PV system is −7.9%. With an increasing number of electric vehicles in a municipality, the differentials in quartiles three and four show a diminishing negative effect (in comparison to the first quartile). Similarly, Panel B shows a strong negative effect for the first quartile (−5.1% for municipalities with the lowest change in electric vehicles). Increasing lived preferences for sustainability compensate for this negative effect, as shown by a significant differential of 3.9%-points in the quartile of municipalities with the highest change in electric vehicles between 2015 and 2021.

5.4. Municipality differences and the view at PV systems

Solar energy production potential: Negative rent externalities of PV systems may go in hand with the suitability of a municipality to adapt to solar energy production. Hence, we follow the same approach as in Section 5.3 and we split our residential rent observations along quartiles of municipalities with the lowest to the highest solar energy production potential. Regression results in Panel A of Table 8 show again a causal pathway: The first quartile has a strong negative estimate of rent externalities of PV systems, which diminishes in higher quartiles (differential). This may signal that municipalities with higher solar potential are more likely to adopt PV systems, as these installations are recognized as efficient ways to produce electricity. As outlined

[18] For example, in St. Gallen, the local electricity provider (St.Galler Stadtwerke) operates several large PV installations across the city and founded the *St.Galler Solar Community*. This association allows local residents to buy shares or individual panels of these large PV systems to benefit from their electricity production until the end of the panel's lifespan.

Table 7
External effect of PV systems on residential rents – Lived preferences.

	Residential rents
Panel A: HTE — Number (#) of registered electric vehicles 2015	
View at a PV system (# electric vehicles (Q1))	−0.079*** (0.021)
View at a PV system (# electric vehicles (Q2): Δ)	−0.004 (0.024)
View at a PV system (# electric vehicles (Q3): Δ)	0.040* (0.021)
View at a PV system (# electric vehicles (Q4): Δ)	0.068*** (0.021)
Year fixed effects	18
Building fixed effects	57,964
Observations	620,937
Panel B: HTE — Change (%) in registered electric vehicles 2015–2021	
View at a PV system (change in electric vehicles (Q1))	−0.051*** (0.013)
View at a PV system (change in electric vehicles (Q2): Δ)	−0.008 (0.017)
View at a PV system (change in electric vehicles (Q3): Δ)	0.001 (0.013)
View at a PV system (change in electric vehicles (Q4): Δ)	0.039*** (0.013)
Year fixed effects	18
Building fixed effects	57,964
Observations	620,937

This table lists the results of staggered difference-in-differences regressions for estimating the causal pathway of the external effect of a PV system on residential rents. Quartiles at the municipality level are based on the number of electric vehicles in a municipality (Panel A) as well as changes in registered electric vehicles (in %) from 2015 until 2021 (Panel B), reflecting the municipal population's lived preferences for sustainability. HTE is short for heterogeneous treatment effects, and Δ denotes a differential with the respective first quartile. The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors at the building level are reported in parentheses. The adjusted within R^2 for all regressions is approximately 0.35. *** and * denote statistical significance at the 1 % and 10% level.

Table 8
External effect of PV systems on residential rents – Municipal differences.

	Residential rents
Panel A: HTE — Solar energy production potential (roofs and facades)	
View at a PV system (potential (Q1))	−0.082*** (0.014)
View at a PV system (potential (Q2): Δ)	0.006 (0.014)
View at a PV system (potential (Q3): Δ)	0.037*** (0.014)
View at a PV system (potential (Q4): Δ)	0.074*** (0.014)
Year fixed effects	18
Building fixed effects	57,853
Observations	620,416
Panel B: HTE — Housing vacancy rate (%) 2006–2021	
View at a PV system (vacancy (Q1))	−0.001 (0.002)
View at a PV system (vacancy (Q2): Δ)	−0.009*** (0.003)
View at a PV system (vacancy (Q3): Δ)	−0.033*** (0.004)
View at a PV system (vacancy (Q4): Δ)	−0.032*** (0.004)
Year fixed effects	18
Building fixed effects	57,853
Observations	620,416

This table lists the results of staggered difference-in-differences regressions for estimating causal pathways of the external effect of a PV system on residential rents. Quartiles at the municipality level are based on the solar energy production potential for roofs and facades (Panel A), respectively, and the average vacancy rate throughout the years 2006 to 2021 (Panel B) in each municipality (lowest to highest). HTE is short for heterogeneous treatment effects, and Δ denotes a differential with the respective first quartile. The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors at the building level are reported in parentheses. The adjusted within R^2 is approximately 0.35. *** denotes statistical significance at the 1% level.

in Section 3.4, the metric on solar energy production potential is also heavily correlated with urban density. Hence, these quartiles are an indicator of a split across urban density. Less dense areas (with low potential) have a strong negative effect due to their more rural landscape, whereas highly dense areas (with high potential) have a small or no effect due to the cityscape where PV installations are more likely to blend in.

Rental demand elasticities: Further, we divide our sample of rental observations based on the quartiles of municipalities' average vacancy rates in the residential real estate market from 2006 to 2021. In doing so, we can investigate the impact of varying rental market tightness. Municipality quartiles with a low vacancy rate are characterized by a relatively "tight" rental market where the demand for rental housing is price inelastic. In contrast, quartiles with a high vacancy rate are municipalities with a comparatively "elastic" rental market where the demand for rental housing is price elastic. In Panel B of Table 8, the estimates demonstrate a causal pathway along the local residential real estate market vacancy rate or the local demand elasticity of housing. The first quartile (low vacancy rate) shows a very small and insignificant coefficient, indicating that when the demand elasticity for housing is relatively inelastic, renters cannot penalize the view at a PV system. In contrast, when the demand for housing is more elastic (high vacancy rate), negative externalities of PV installations are present in the market. Hence, if renters have the market power, a rent discount materializes when a residential property has a view at a PV system.

Table 9
External effect of PV systems on residential rents – PV-building type.

	Residential rents
Panel A: Residential buildings	
View at a PV system	−0.013*** (0.002)
Year fixed effects	18
Building fixed effects	43,216
Observations	448,843
Panel B: Mixed-use building	
View at a PV system	−0.004 (0.003)
Year fixed effects	18
Building fixed effects	23,390
Observations	279,364
Panel C: Non-residential building	
View at a PV system	−0.008** (0.004)
Year fixed effects	18
Building fixed effects	21,079
Observations	249,851

This table lists the results of various staggered difference-in-differences regressions for the estimation of the external effects of PV systems on residential rents. The estimation samples are stratified by the type (purpose) of buildings on which PV systems are installed. The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors at the building level are reported in parentheses. The control group in each regression includes all 140,929 never-treated observations. The adjusted within R^2 for all regressions reported is in the range of 0.35 to 0.37. *** and ** denote statistical significance at the 1 % and 5% level.

Table 10
External effect of PV systems on residential rents – New vs. Old PV-buildings.

	Residential rents
Panel A: PV on a new building	
View at a PV system	−0.007** (0.003)
Building fixed effects	21,391
Observations	238,654
Panel B: PV on an old building	
View at a PV system	−0.014*** (0.002)
Building fixed effects	50,328
Observations	523,285

This table lists the results of various staggered difference-in-differences regressions for the estimation of the external effects of PV systems on residential rents. More specifically, these estimations relate a PV system's start of operation to the final construction year of buildings on which PV systems are installed. In Panel A, observations are considered as treated if they have a view at a PV system which is installed on a new building (the start of its operation is identical to the final construction year of the building it sits on). In Panel B, the PV is installed on an existing/old building (the start of its operation is not equal to the building's final construction year). The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors at the building level are reported in parentheses. The control group in each regression includes all 140,929 never-treated observations. The adjusted within R^2 for all regressions reported is in the range of 0.35 to 0.37. *** and ** denote statistical significance at the 1 % and 5% level.

5.5. Robustness checks

PV-building type: To address concerns about potential confounding influences from architectural features and building amenities, we conduct a robustness test that uses information from the Swiss Building Census to stratify the estimation sample by the type of building on which PV systems are installed. Table 9 presents these results. Panel A shows that for purely residential buildings carrying PV systems, the negative rent externality remains at −1.3%, identical to our baseline estimate. This finding is crucial as purely residential buildings provide no commercial amenities or services that could confound our estimated negative externalities of PV systems. In contrast, Panel B reveals that the negative effect is substantially attenuated to −0.4% (and less precisely estimated) for mixed-use buildings, while Panel C shows an effect of −0.8% for non-residential buildings. This gradient from residential buildings to non-residential and mixed-use buildings suggests that the negative view externality is partially offset when the building carrying the PV system provides amenities such as retail shops, services, or employment. Crucially, the persistence of the full negative effect for purely residential buildings suggests that our results are not driven by general building unattractiveness, densification effects, or correlations between architectural style and PV adoption.

New vs. existing PV-buildings: To further disentangle negative externalities of PV systems from architectural features and possible densification effects, we now differentiate PV systems that are installed on newly constructed buildings or retrofitted onto existing structures using information from the Swiss Building Census. Table 10 presents results that strongly support our identification strategy. Panel A shows that for PV systems installed on buildings constructed in the same year as the PV commissioning (new buildings), we find a statistically significant negative effect of −0.7%. Notably, Panel B shows that PV systems retrofitted onto existing buildings generate an even larger negative externality of −1.4%. This pattern suggests that our results are not driven by densification, poor overall building aesthetics, or the correlation between architectural style and the propensity for PV adoption. If these confounding factors were the primary drivers, we would expect to find the largest effects for new buildings with PV systems. Instead, the larger effect for retrofitted installations, where only the PV system changes while the underlying building remains the same, provides an even cleaner identification of the visual externality. Table A.3 in the Appendix further investigates this retrofitting channel by examining PV installations across different construction periods of existing buildings (again using Swiss Building Census definitions). While we observe the largest negative effects for buildings constructed between 1970–2010 (−1.4% to −1.8%), statistically significant negative externalities persist across all but one construction periods, including older buildings from 1610–1918 (−0.9%).

Treatment Leads: To address concerns about potential time lags between commissioning and the actual installation of a PV system, as well as timing precision issues, we conduct a treatment leads analysis presented in Table 11. Panel C reveals a pattern of anticipatory effects leading up to PV commissioning, with statistically significant negative coefficient estimates that diminish in magnitude from −0.009 one year before commissioning to −0.005 two years prior, and virtually zero in the third year before commissioning. This pattern is consistent with several potential mechanisms that are linked to PV installations: First, PV systems may become visible during construction phases before official commissioning, which means that some properties classified as control observations are already experiencing visual treatment, introducing a downward bias in the estimated treatment effect in absolute terms (rendering our baseline estimate of −1.3% conservative). Second, broader building refurbishment or construction activities preceding PV installation, such as scaffolding, noise, or general construction disruption, create additional negative externalities that are captured by the lead coefficients. For new buildings, visible development activity may require rent discounts even before PV installation begins. Importantly, Panels A and B show that omitting observations one or two periods prior to treatment indeed increases the estimated treatment effect to −1.4% and −1.6%, respectively, confirming that anticipatory effects lead to an underestimation of the true externality. Given our annual measurement precision, some observations within a treatment year may occur months before actual commissioning but are coded as treated, introducing noise that further attenuates our estimates. This analysis, therefore, suggests that our baseline result of −1.3% represents a lower bound of the true negative externality from viewing PV systems.

Additional Explorations: To further address concerns about architectural confounders and unobserved heterogeneity, Table 12 presents results using PV-system fixed effects that control for all time-invariant characteristics specific to individual PV installations and their immediate surroundings. Panel A replicates our baseline specification with

Table 11
External effect of PV systems on residential rents – Treatment leads.

	Residential rents
Panel A: Dropping observations one period before treatment date	
View at a PV system	−0.014*** (0.002)
Year fixed effects	18
Building fixed effects	57,572
Observations	601,272
Panel B: Dropping observations two periods before treatment date	
View at a PV system	−0.016*** (0.002)
Year fixed effects	18
Building fixed effects	57,123
Observations	582,782
Panel C: Treatment leads	
View at a PV system	−0.017*** (0.002)
View at a PV system (lead 1)	−0.009*** (0.002)
View at a PV system (lead 2)	−0.005*** (0.002)
View at a PV system (lead 3)	−0.003 (0.002)
View at a PV system (lead 4)	−0.002 (0.002)
View at a PV system (lead 5)	0.001 (0.002)
Year fixed effects	18
Building fixed effects	57,969
Observations	621,010

This table lists the results of various staggered difference-in-differences regressions for the estimation of the external effects of PV systems on residential rents. Panels A and B cover restricted estimation samples without treated observation units one or two periods prior to PV installations' date of commissioning. Panel C examines the full estimation sample to analyze treatment effects over the five periods preceding the treatment timing considered so far (i.e., PV installations' date of commissioning). The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. Cluster-robust standard errors at the building level are reported in parentheses. The adjusted within R^2 for all regressions is 0.35. *** denotes statistical significance at the 1 % level.

building fixed effects and compares it to the use of PV-system fixed effects, which yield identical results. Panel B restricts the analysis to ever-treated observations only, ensuring each unit is unambiguously linked to a specific PV system whose architectural style, building aesthetics, and neighborhood characteristics can be controlled for through PV-system fixed effects. The results reveal that when controlling for these PV-specific unobservables, the negative externality increases from −1.4% to −1.8%, suggesting that our baseline estimates may be conservative due to uncontrolled positive amenities in some PV neighborhoods. Panel C further demonstrates robustness by focusing on smaller PV systems (<30 kVA), which comprise approximately 60% of our estimation sample and 78% of ever-treated observations. Even for smaller, potentially less visually intrusive installations, we find substantial negative effects of −1.4% (building FE) to −1.6% (PV-system FE), which confirms that our findings are not driven by large, industrial-scale installations but persist across the full spectrum of residential PV systems. In line with the Swiss Federal Office of Energy's estimated coverage of about 97% of small-scale PV systems in the EPA database, this robustness check also shows that our results are not suffering from a sample selection bias due to voluntary registrations of small-scale PV systems.

6. Conclusion

This study aims to identify potential external effects of PV systems on residential rents. In particular, our analysis investigates potential positive or negative externalities of having a view at PV installations. Our empirical results demonstrate that the view (partially impaired and unimpaired) at a PV system leads to a depreciation of residential rents. This negative impact is stronger for the view at multiple PV systems as well as in situations where seeing a PV is more likely. However, the effect is not driven by large and close PV systems, possibly due to the potential benefits of these installations, such as electricity provision for surrounding tenants. Moreover, the negative effect is stronger for properties with scenic views. Negative rent externalities of PV installation are offset by the internal PV system of the dwelling. By using municipal voting results on the Swiss Energy Act 2017 and the Swiss CO_2 Act in 2021, we show that lower stated preferences for sustainability are a potential driver of negative external effects of PV installations on rents. Analogously, lived preferences for going green, measured by the number and change of registered electric vehicles, allow estimating a similar causal pathway of our main effect. In addition, a municipality's solar energy production potential yields insights into the dynamics of residential rent externalities of PV systems across urban, sub-urban, and rural areas. Finally, we also show that negative rent externalities of PV systems go hand in hand with an elastic demand for housing.

Our results have implications for both real estate investors and policymakers. PV systems create negative externalities for surrounding rental buildings, which induces a lower rental income for investors. However, this negative impact is more than outweighed if a dwelling has an internal PV system or if it may reap benefits from large PV installations in its vicinity. Hence, it is likely that any such negative externalities on tenants disappear if the adoption of PV systems on residential properties benefits not just renters or owners of a house on which those systems are installed but also residents close by. For policymakers, our study highlights the importance and necessary recognition of neighbors as stakeholders in the approval process of PV systems. For example, Switzerland introduced mandatory PV installations for new buildings with large rooftops or fronts (more than 300 m^2 in September 2023). However, to date, this policy fails to address the externalities of PV systems and how the generated power is distributed in a neighborhood, leaving room for further improvements in formulating appropriate policies to reduce the impact on immediate neighbors. Future policies must not exclusively account for the exposition of PV installations and, thus, the electricity production of PV systems, but also their visibility and the allocation of benefits that may be reaped from such power production facilities. In doing so, policymakers can make use of the significant spatial heterogeneity of the effect to reduce the negative impact on the rental housing market. For example, PV adoption policies may focus on areas with higher stated and lived preferences for sustainability, a higher solar production potential (urban areas), or an inelastic demand for housing.

Table 12
External effect of PV systems on residential rents – Additional explorations.

	Residential rents
Panel A: All observations	
View at a PV system (building fixed effects — baseline)	−0.013*** (0.002)
View at a PV system (PV-system fixed effects)	−0.013*** (0.003)
Year fixed effects	18
Observations	621,010
Panel B: Ever-treated observations	
View at a PV system (building fixed effects)	−0.014*** (0.002)
View at a PV system (PV-system fixed effects)	−0.018*** (0.002)
Year fixed effects	18
Observations	480,081
Panel C: Ever-treated observations (PV power production $\leq 30kVA$)	
View at a PV system (building fixed effects)	−0.014*** (0.002)
View at a PV system (PV-system fixed effects)	−0.016*** (0.003)
Year fixed effects	18
Observations	374,122

This table lists the results of various staggered difference-in-differences regressions for the estimation of the external effects of PV systems on residential rents. The estimation sample in Panel A are all observations of the full sample, and Panel B covers the sub-sample of ever-treated observations. Panel C further restricts this sub-sample of ever-treated observations to units with a view at smaller PV installations (PV power production <30 kVA). In each panel, the external effect is estimated with either building fixed effects or PV-system fixed effects. The dependent variable is the natural logarithm of residential rents. All regressions include the full set of control variables. In regressions that employ PV-system fixed effects, further building-level characteristics (the number of storeys and the building period) as well as a neighborhood-type indicator are added as controls. Cluster-robust standard errors at the building level or at the PV-system level are reported in parentheses. The number of building (PV-system) fixed effects is 57,969 (4,246) in Panel A, 46,583 (4,245) in Panel B, and 37,623 (3,687) in Panel C. The adjusted within R^2 for regressions including building (PV-system) fixed effects is 0.35 (0.26) in Panel A, 0.35 (0.32) in Panel B, and 0.35 (0.31) in Panel C. *** denotes statistical significance at the 1 % level.

CRediT authorship contribution statement

Roland Füss: Writing – review & editing, Writing – original draft, Methodology, Conceptualization, Supervision, Project Administration. **Kathleen Kürschner Rauck:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Methodology, Formal analysis, Conceptualization. **Alois Weigand:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.regsciurbeco.2025.104138.

Data availability

The data that has been used is confidential.

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