Residential Rent Externalities of Photovoltaic Systems: The Relevance of View

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This Version: September 2024

Abstract

We study how photovoltaic (PV) systems externally affect the rents of residential dwellings. By creating a three-dimensional topographical model of our study areas in Switzerland, we model each building's view at surrounding PV installations and merge this data with rental price observations. In the hedonic difference-in-differences regressions, we provide evidence of how this view (impaired or unimpaired) on a PV system is associated with lower residential rents. This effect is stronger for the view at multiple PV systems rather than at a single one, in situations where seeing is more likely, and where PV installations disrupt a scenic view. However, price penalties are attenuated if rental dwellings have their own PV system or if neighboring properties have large PV systems, which may benefit surrounding tenants in terms of electricity provision. Furthermore, by using municipal voting results on the Swiss Energy Act 2017 and the Swiss CO_2 Act in 2021, we show how stated preferences for sustainability drive the external effects of PV systems on rents. We document a similar causal pathway for lived preferences measured by the number and change in electric vehicles in Swiss municipalities, for municipalities' solar energy production potential, as well as municipalities' local demand elasticities for housing.

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[*] **Acknowledgments:** The authors are grateful to Martin Brown, Simon Büchler, Maximilian von Ehrlich, Ralf Laschinger, Max Masterson, Brian Melzer, Wei Lin, Christian Opitz, Markus Schmid, Maxence Valentin, and the participants at the 2022 NTNU Business School Conference, the 2023 NHH Brown Bag Seminar Series, the 2023 HSG Econ-Finance Seminar, the 2024 Cambridge Land Economy Research Seminar, the 2024 ARES Doctoral Program, the 2024 CRED-MIT Workshop on Real Estate Economics, the 2024 AREUEA International Conference, the 2024 World Finance Conference, and the 2024 Annual GRASFI Conference for helpful comments. Furthermore, we thank Daniel Sager for providing data on residential rents and the Swiss Federal Office of Energy (SFOE) for funding this project.

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Abstract

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JEL Classification: Q40, R11, R32.
Keywords: Photovoltaic Systems; Renewable Energy Infrastructure; Residential Real Estate; Rents; View Modeling.

1 Introduction

View matters in residential real estate markets. 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 small-scale energy infrastructure. Finally, we investigate to which extent stated and lived preferences for sustainability in municipalities and a municipality's solar energy production potential drive our results on 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 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 averaged-sized PV installation with a potential of 8-10 kilowatt-peak can generate electricity worth CHF 1,640 to CHF 2,050 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 an 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 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 in hand with an elastic demand for housing (approximated by a municipality's vacancy rate in residential housing).

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, Braun, and Kvasnicka, 2017) or wind turbines (Skenteris, Mirasgedis, and Tourkolias, 2019) on housing is well documented, there are relatively few studies on how the housing market reacts to the installation of PV systems. In the context of large-scale PV projects, Elmallah, Hoen, Fujita, Robson, and Brunner (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 in 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 small-scale 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.

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 model 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, Kok, and Quigley, 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, Kok, and Quigley, 2013; Wiencke, 2013; Kahn, Kok, and Quigley, 2014; Ramos, Gago, Labandeira, and Linares, 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, Firestone, Rand, Elliot, Hübner, Pohl, Wiser, Lantz, Haac, and Kaliski, 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, Kok, and Quigley, 2013). These findings are in line with Brändle, Füss, Schläpfer, and Weigand (2022), 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, Zivin, Costa, and Kahn, 2012; Wen, Dallimer, Carver, and Ziv, 2018) and between 4 % and 6 % per watt premium (Hoen, Wiser, Thayer, and Cappers, 2013) after the installation of a PV system. Overall, the findings on the installation of solar rooftops consistently 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.[1] Second, the authors propose that

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[1] Zheng, Wu, Lin, Jia, and Wei (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.

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 important to fully understand 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 old 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. We choose these areas due to their availability of open-source government data. 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 rent externalities of PV systems. The selection of study areas is also relatively homogenous 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.

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 $30kVA$ are included. Small-scale PV systems ($> 2kVA$) 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.[2]

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.

3.2 3D Topographical Data

To create the 3D model of our study areas in Figure 1, we collect three datasets from the Swiss Federal Office of Topography.[3] 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.

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[2] 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 in Switzerland due to the high share of subsidization.

[3] 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 is updated every six years.

[INSERT FIGURE 1 HERE]

Buildings, bridges, and towers have exact so-called polyhedral surfaces in Figure 1. In contrast, the topography is modeled with an accuracy of 5 meters. 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.[4] These listings are taken from several online real estate market platforms such as *ImmoScout24.ch* or *Homegate.ch*.[5] 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.[6] (3) Listings must allow for precise geo-coding and have an exact address. (4) Residential rent observations lie within an observation circle of 500m for integrated PV systems and 2km for non-integrated PV systems.

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[4] The time horizon of our dataset on Swiss residential rents spans the COVID-19 pandemic. According to Balemi, Füss, and Weigand (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, Füss, and Weigand (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.

[5] 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.

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

[INSERT TABLE 1 HERE]

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.

[INSERT TABLE 2 HERE]

First, we are particularly interested in the municipal voting results of two referendums reflecting stated preferences for sustainability.[7] 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

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[7] As outlined by Stutzer and Lalive (2004) as well as Brändle, Füss, Schläpfer, and Weigand (2022), 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.

% (Q1) to 69.9 % (Q4). In a second referendum on June 13, 2021, the Swiss electorate rejected the Federal Act on the 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 until 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 1,130 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 Figure 2.

[INSERT FIGURE 2 HERE]

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.[8]

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 if 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.[9] 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

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

[9] 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.

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 of our study areas (see Section 3.2). This setting allows classifying the view 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.

[INSERT FIGURE 3 HERE]

Figure 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, grey, or black cannot see the PV system as their view might be blocked by buildings, trees, or other objects.

[INSERT FIGURE 4 HERE]

Figure 4 indicates that multiple PV systems can be found in most areas.[10] 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 another score for seeing large and close PV systems as well as a score for the overall number of PV installations that can be seen from any one building in our dataset, respectively.

4.2 Treatment Groups

To define treated observations for our difference-in-differences model (see Subsection 4.3), we take the date of commissioning of each PV system as the treatment date. To get a

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[10] 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.

better understanding of this treatment while modeling the view at PV systems, we zoom into the area of the blue circle in Figure 4 (bottom left from center) to obtain Figure 5.

[INSERT FIGURE 5 HERE]

In Panel A of Figure 5, an observation circle with a cut-off distance of 500m is drawn around a specific PV system that 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.

[INSERT FIGURE 6 HERE]

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. Figure 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 10m 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 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 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.

[INSERT TABLE 3 HERE]

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 the following staggered difference-in-differences model, which includes a full set of hedonic characteristics as well as time and building fixed effects:[11]

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

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

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[11] Usually, a PV installation is combined with a heating pump or a hybrid heating system. Heating systems are internal small-scale energy infrastructures that might additionally affect the impact of PV systems on residential rents (see, e.g., Kijo-Kleczkowska, Bruś, and Więciorkowski (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).

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 Equation (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 (covariates are of minor importance in our model). To verify the validity of this assumption, we employ parallel trend tests in all re-estimations of Equation (1). 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 Equation (1) allows a more robust estimation similar to repeat cross-section data.[12] 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.

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[12] 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.

5 Empirical Results

5.1 Baseline Effects of Viewing PV Systems

Regression results of estimating Equation (1) are listed in Table 4. As outlined in Subsection 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.

[INSERT TABLE 4 HERE]

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 Equation (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 averaged-sized PV installation with a potential of 8-10 kilowatt-peak can generate electricity worth CHF 1,640 to CHF 2,050 (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 (for the Environment, 2024).[13] Hence, the decrease in rental income when having a view at a PV system is compatible large when compared to electricity production and carbon reductions as multiple apartments can see the installation simultaneously.

[INSERT FIGURE 7 HERE]

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[13] 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.

Figure 7 depicts the disaggregated biennial ATET in the context of residential rents. These results are again based on our staggered difference-in-differences regression with building and time-fixed effects and illustrate 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.

[INSERT FIGURE A.1 HERE]

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, a view to the North is already priced in before the treatment date.

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 Equation (1).[14] 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.

[INSERT TABLE 5 HERE]

Likely vs. less likely view at a PV: In Panel B, 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

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

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 Figure 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 C 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.

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

Buildings with vs. without own PV: In Panel E of Table 5, we test whether the rent externalities of having a view at a PV installation changes for dwellings that house their own PV system. Residents of buildings with an installation might be more positively inclined toward seeing other PV systems. 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.

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 F 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 G 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, Füss, Schläpfer, and Weigand (2022). 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 a different stated political attitude 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. 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.

[INSERT TABLE 6 HERE]

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 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 compensates 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.

[INSERT TABLE 7 HERE]

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 small-scale PV systems as these installations are recognized as efficient ways to produce electricity. As outlined 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.

[INSERT TABLE 8 HERE]

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.

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 an 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 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 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, 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.

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Tables

Table 1: Summary Statistics - Residential Rents

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.

	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

Table 2: Summary Statistics - Municipality Characteristics

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.

	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

Table 3: Residential Rent Observations with a View at PV systems

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.

	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
Unikely 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 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 own PV	0.584	0.493	0	1
View at a PV system with own PV	0.005	0.073	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

Table 4: External Effects of PV Systems on Residential Rents – Baseline

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 parenthesis. The number of building fixed effects is 57,969. ***, **, and * denote statistical significance at the 1 %, 5 %, and 10 % level.

	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	Yes	
Building fixed effects	Yes	
Observations	621,010	
Adjusted within R^2	0.352	

Table 5: External Effect of PV Systems on Residential Rents – View Types

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-G). 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 parenthesis. The number of building fixed effects in Panels A-G is 57,969. 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 %, 5 %, and 10 % level.

	Residential Rents
Panel A: Baseline	
View at a PV system	-0.013*** (0.002)
Panel B: 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 C: Single vs. multiple	
View at single PV system	-0.010*** (0.003)
View at multiple PV systems	-0.013*** (0.002)
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 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 F: 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 G: 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	Yes
Building fixed effects	Yes
Observations	621,010

Table 6: External Effect of PV Systems on Residential Rents – Stated Preferences

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 parenthesis. The number of building fixed effects in Panel A is 57,725, while Panel B includes 57,964. 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 %, 5 %, and 10 % level.

	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	Yes
Building fixed effects	Yes
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	Yes
Building fixed effects	Yes
Observations	620,937

Table 7: External Effect of PV Systems on Residential Rents – Lived Preferences

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 parenthesis. The number of building fixed effects in Panels A and B is 57,964. The adjusted within R^2 for all regressions is approximately 0.35. ***, **, and * denote statistical significance at the 1 %, 5 %, and 10 % level.

	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	Yes
Building fixed effects	Yes
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	Yes
Building fixed effects	Yes
Observations	620,937

Table 8: External Effect of PV Systems on Residential Rents – Municipal Differences

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, 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 parenthesis. The number of building fixed effects in Panels A and B is 57,853. The adjusted within R^2 is approximately 0.35. ***, **, and * denote statistical significance at the 1 %, 5 %, and 10 % level.

	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	Yes
Building fixed effects	Yes
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	Yes
Building fixed effects	Yes
Observations	620,416

Figures

Figure 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.

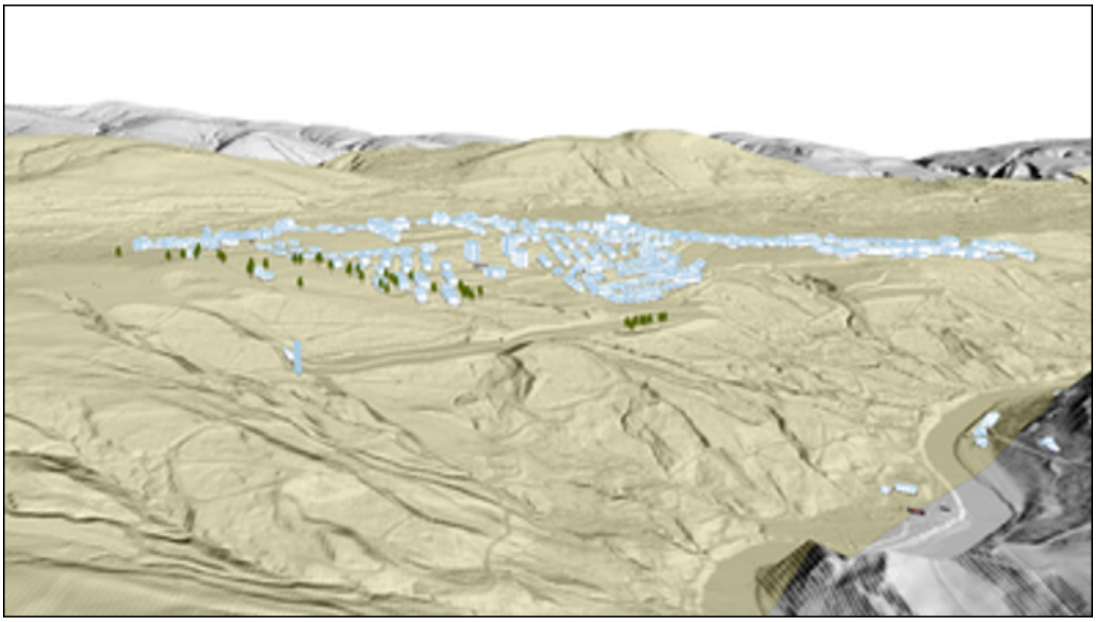


Figure 2: View Modeling – Ray Tracing Method

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.

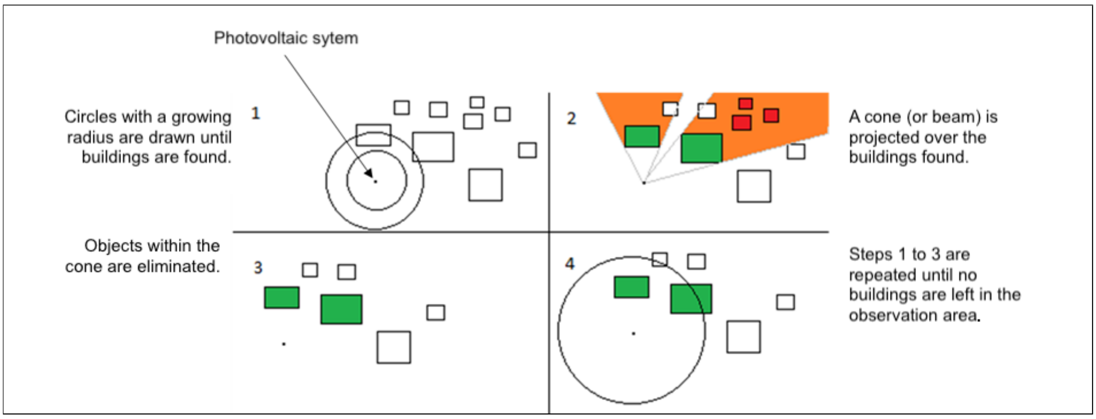


Figure 3: View Modeling – 3D View at a Specific PV System

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, grey, or black. Red areas indicate public land used for roads or sidewalks.

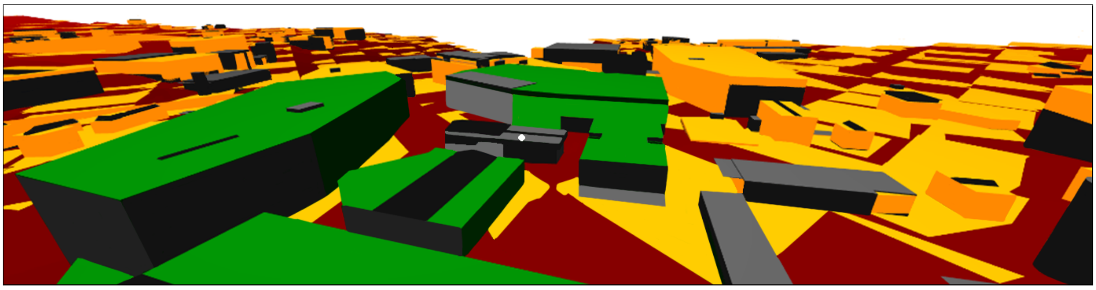


Figure 4: Mapping PV Systems of Different Size

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.

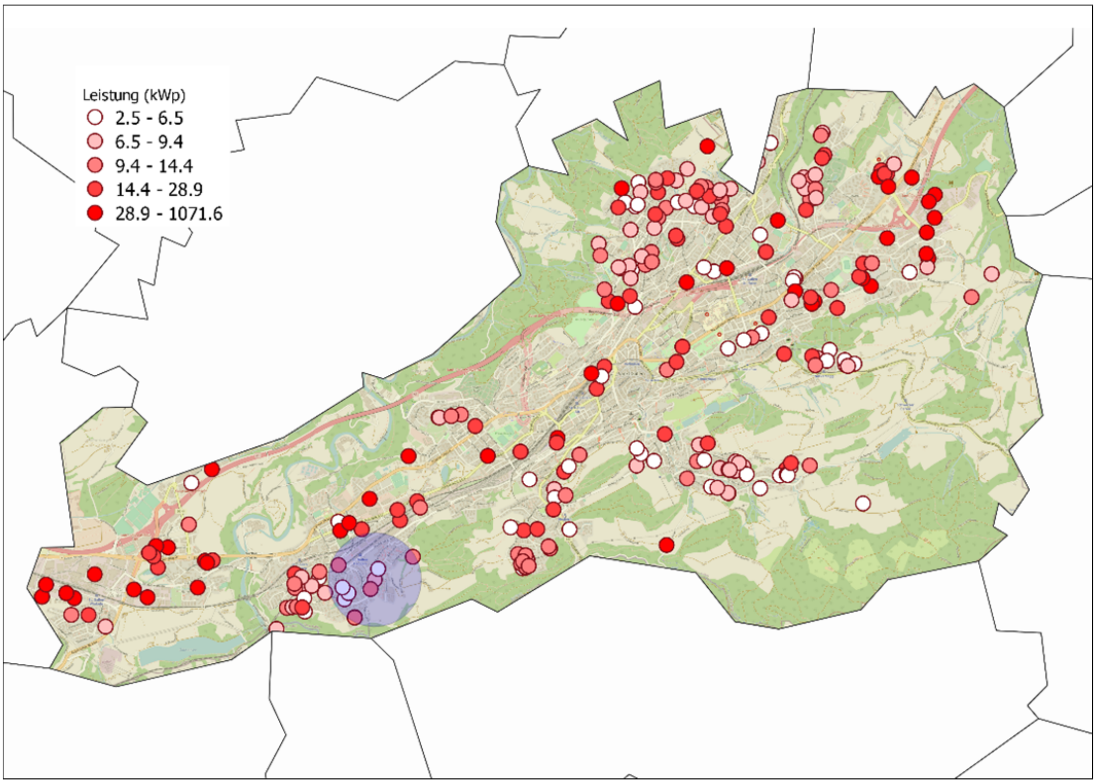
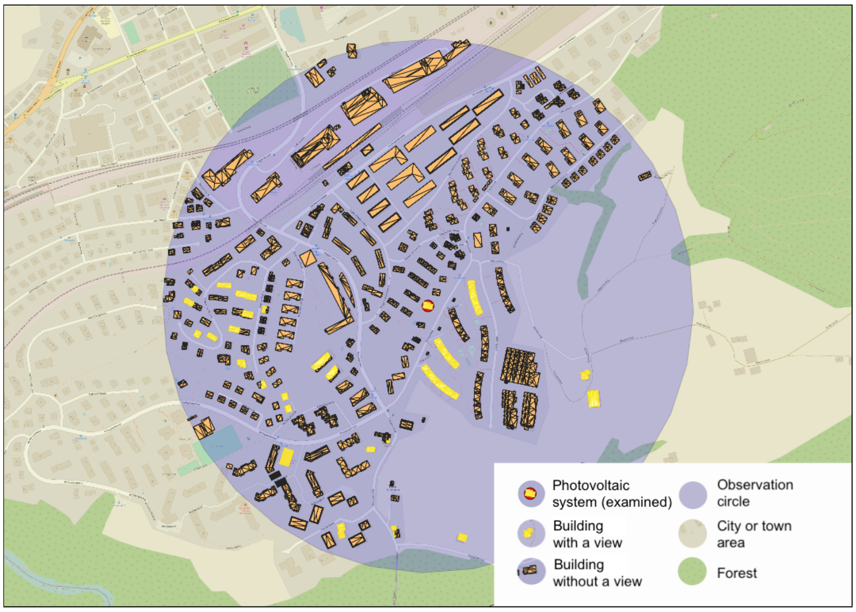


Figure 5: Buildings with a View at a Specific PV Installation

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 500m 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.

Panel A: Impaired and Unimpaired View within Observation Circle



Panel B: Unimpaired View within Observation Circle

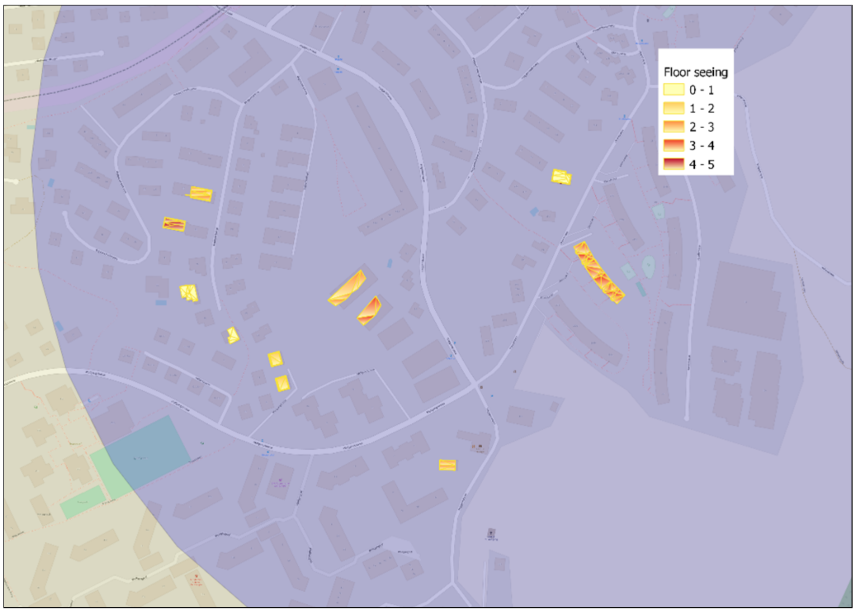


Figure 6: Residential Rents and Buildings with a View at a Specific PV Installation

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.

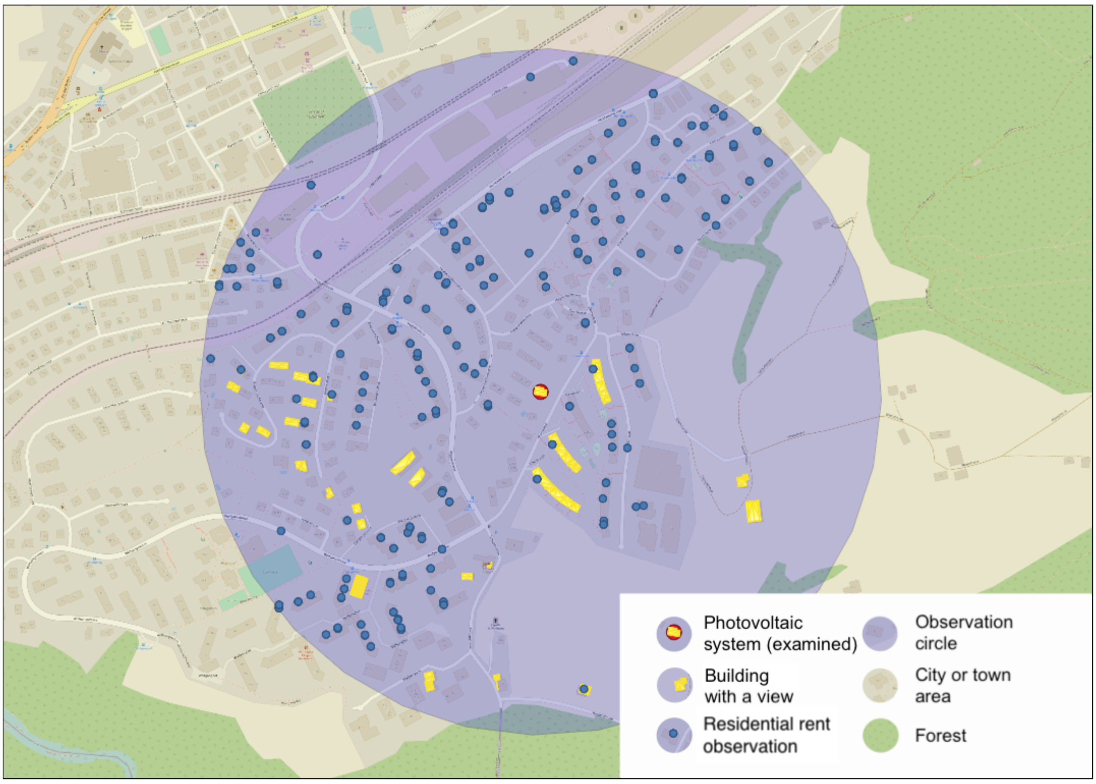
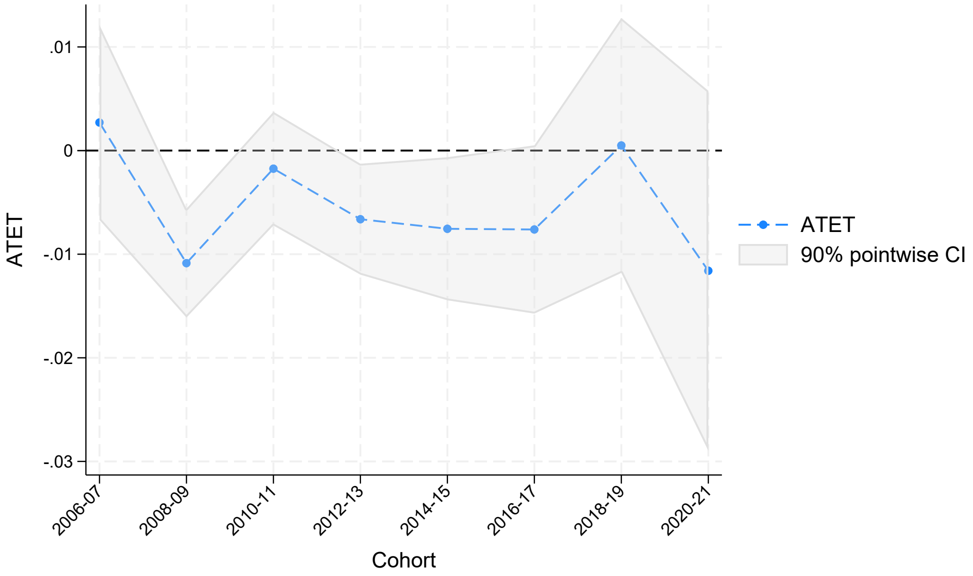


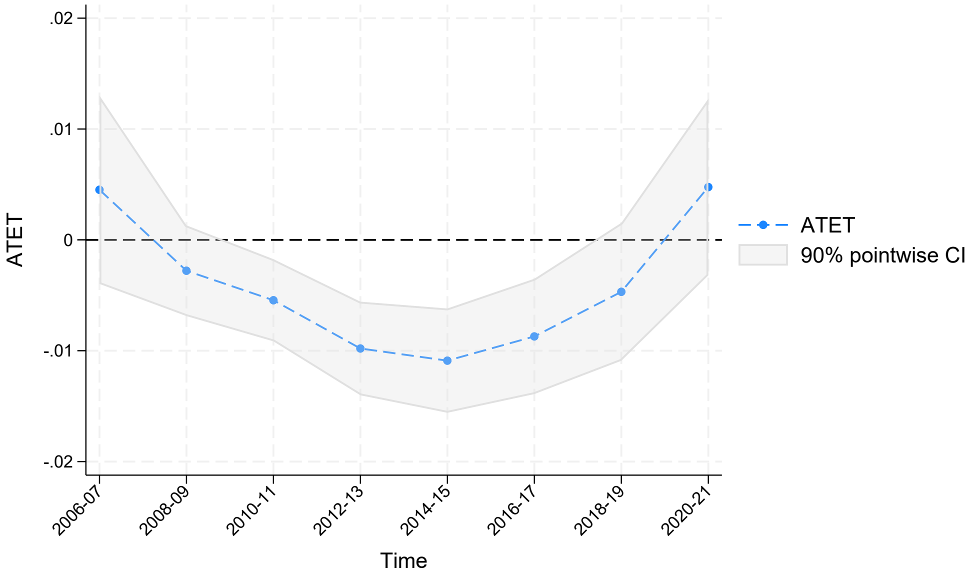
Figure 7: Biennial ATET Plots

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.

Panel A: Cohort-Aggregated Biennial ATET



Panel B: Time-Aggregated Biennial ATET



Appendix for

Residential Rent Externalities of Photovoltaic Systems: The Relevance of View

Abstract

We study how photovoltaic (PV) systems externally affect the rents of residential dwellings. By creating a three-dimensional topographical model of our study areas in Switzerland, we model each building's view at surrounding PV installations and merge this data with rental price observations. In the hedonic difference-in-differences regressions, we provide evidence of how this view (impaired or unimpaired) on a PV system is associated with lower residential rents. This effect is stronger for the view at multiple PV systems rather than at a single one, in situations where seeing is more likely, and where PV installations disrupt a scenic view. However, price penalties are attenuated if rental dwellings have their own PV system or if neighboring properties have large PV systems, which may benefit surrounding tenants in terms of electricity provision. Furthermore, by using municipal voting results on the Swiss Energy Act 2017 and the Swiss CO_2 Act in 2021, we show how stated preferences for sustainability drive the external effects of PV systems on rents. We document a similar causal pathway for lived preferences measured by the number and change in electric vehicles in Swiss municipalities, for municipalities' solar energy production potential, as well as municipalities' local demand elasticities for housing.

JEL Classification: Q40, R11, R32.
Keywords: Photovoltaic Systems; Renewable Energy Infrastructure; Residential Real Estate; Rents; View Modeling.

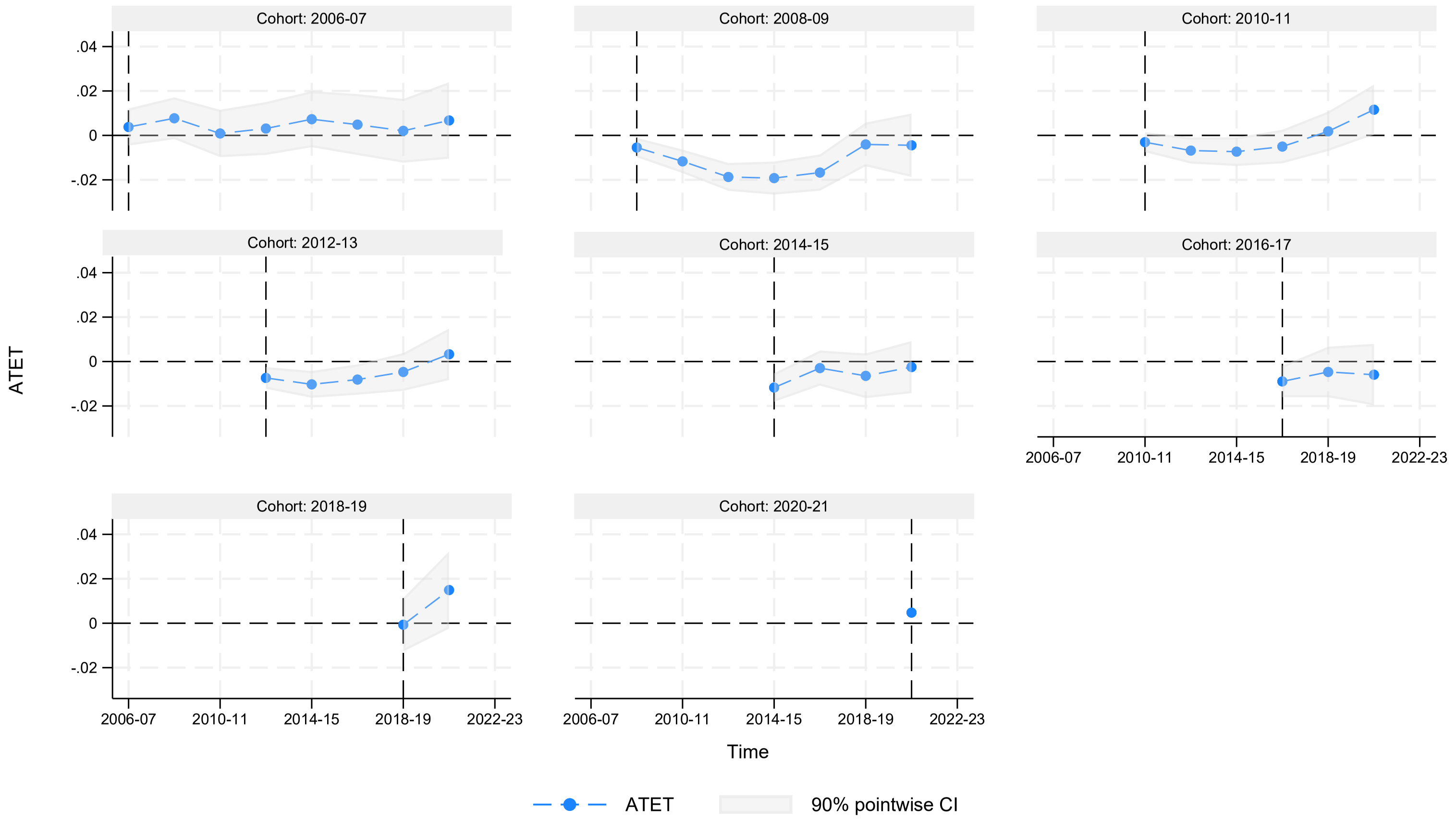
Table A.1: Biennial ATET by Cohort

This table lists the biennial ATET from the staggered difference-in-differences regression to capture the external effects of PV systems on residential rents by cohort. View at a PV system is defined as an impaired and unimpaired view (baseline). Never-treated observations serve as the control group. The number of observations amounts to 621,010. Cluster-robust standard errors (at the building level) are reported in parenthesis. **, and * denote statistical significance at the 5 %, and 10 % level.

	Residential Rents	
Cohort: 2006-07		
2006-07	0.004	(0.005)
2008-09	0.008	(0.006)
2010-11	0.001	(0.006)
2012-13	0.003	(0.007)
2014-15	0.007	(0.008)
2016-17	0.005	(0.008)
2018-19	0.002	(0.009)
2020-21	0.007	(0.010)
Cohort: 2008-09		
2008-09	-0.005*	(0.003)
2010-11	-0.012**	(0.003)
2012-13	-0.019**	(0.004)
2014-15	-0.019**	(0.005)
2016-17	-0.017**	(0.005)
2018-19	-0.004	(0.006)
2020-21	-0.004	(0.009)
Cohort: 2010-11		
2010-11	-0.003	(0.003)
2012-13	-0.007	(0.004)
2014-15	-0.007	(0.004)
2016-17	-0.005	(0.005)
2018-19	0.002	(0.005)
2020-21	0.012	(0.007)
Cohort: 2012-13		
2012-13	-0.007*	(0.003)
2014-15	-0.010**	(0.004)
2016-17	-0.008	(0.004)
2018-19	-0.005	(0.005)
2020-21	0.003	(0.007)
Cohort: 2014-15		
2014-15	-0.012**	(0.004)
2016-17	-0.003	(0.005)
2018-19	-0.006	(0.006)
2020-21	-0.002	(0.007)
Cohort: 2016-17		
2016-17	-0.009*	(0.004)
2018-19	-0.005	(0.007)
2020-21	-0.006	(0.008)
Cohort: 2018-19		
2018-19	-0.001	(0.007)
2020-21	0.015	(0.011)
Cohort: 2020-21		
2020-21	0.005	(0.010)

Figure A.1: Biennial ATET Plots by Cohort

This figure illustrates biennial ATET plots from the staggered difference-in-differences regression to capture the external effects of PV systems on residential rents by cohort. View at a PV system is defined as impaired and unimpaired view. Never-treated observations serve as the control group.



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