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Abstract

Conflicting societal goals can lead to national and local policies that are at odds with each other. National policies promoting the adoption of solar photovoltaics may be counteracted by local policies defining the aesthetics of the built environment. As solar photovoltaic energy approaches grid parity globally, non-pecuniary barriers to the adoption of this important renewable energy source become increasingly salient. Using a unique survey of municipalities regarding such building codes and administrative data on all solar installations in Germany, a leader in solar adoption, we document the impact that municipalities amending their building codes to restrict solar installations, often with an eye toward preserving the historical nature of the town, has on solar adoption. We find that municipalities that implement solar policies have 10.4 percent less solar photovoltaic capacity than municipalities in the control group. We confirm our results when applying spatial techniques and analyzing the impact of such policies on regulated areas within municipalities.

JEL-Codes: D620, H770, Q480, Q580, R520.

Keywords: building codes, solar photovoltaics, policy evaluation, NIMBY.

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1. Introduction

Competing societal goals give rise to policy trade-offs. For instance, policy goals defined at the national, or even global level, may conflict with policy goals at the very local level. Local policies that challenge national policy are sometimes referred to as NIMBYism, from 'not in my backyard.' In this paper, we show that municipal policies reduce the pace of solar capacity expansion.

Many governments recognize the necessity of expanding renewable energy to tackle climate change, as well as to ensure energy security in an age of renewed geopolitical uncertainty. Renewable energy targets are often determined by carbon emission reductions goals, 'Nationally Determined Contributions,' under the Paris Agreement. The share of renewable electricity has been increasing substantially across the globe, yet most countries are relatively far from reaching their goals. On a positive note, the widespread use of subsidies to renewable energy has contributed to a decrease in the price of solar installations, exceeding expectations (Creutzig et al., 2017; REN21, 2022). As solar energy reaches grid parity in many countries, governments are phasing out the subsidy schemes used to promote the installation of solar photovoltaics (PV), which are often expensive and regressive (Marcantonini and Ellerman, 2015; Borenstein, 2017). This new era comes with new challenges for academics and policymakers. Assessing the role of non-price obstacles to the adoption of solar PV represents, arguably, the new frontier in research and policymaking. Here, we focus on the role of local policies, whose aims conflict with the national goal of spurring the adoption of solar PV.

Our paper identifies trade-offs between municipal building code requirements and polices aimed at defining the aesthetics of German towns, in particular with an eye toward historical preservation, and the adoption of solar PV. To do so, we combine geolocalized data on the universe of solar installations in Germany, with a unique survey on municipalities' current and past building codes affecting the adoption of solar PV. While technological advances in the market for solar PV have been consistently improving the aesthetics of solar installations, we observe that German municipalities have become increasingly restrictive in regulating the installation of solar PV. Hence, while from a technological perspective such trade-offs may be in the process of becoming obsolete, from a policy perspective analyzing the role of building codes on the adoption of solar PV, an aspect largely neglected so far, seems to be more relevant than ever.

Germany, one of the countries in the world with the highest penetration of solar energy and one of the most mature markets for solar PV, is an ideal place to assess the role of building codes in preventing the adoption of solar PV. Additionally, Germany is particularly well suited to this inquiry because the country has a decentralized administrative structure, which gives municipalities substantial leeway beyond the federal and state building codes. A significant share of German municipalities have implemented building codes that explicitly or implicitly regulate the installation of solar panels on buildings, with this share increasing over time.

To date, no comprehensive registry of municipal solar policies exists. A major contribution of our study is to create such a registry based on survey responses from municipal officials. In this survey, delivered to all municipalities in Germany, we ask for information about how the local building code treats the installation of solar panels. Regulations of solar installations in some cases include explicit bans in certain areas or the entirety of the municipality. Some other municipalities have more subtle provisions, for example, such that solar installations cannot be visible from the street. We obtained information on when municipal policies became effective, as well as on past policies no longer in effect. We match this information to federal data resulting from the mandatory reporting of the location and technical specification of solar panels connected to the electric grid and municipal-level demographic and electoral statistics.

Municipalities do not randomly implement solar policies. First, our study explores the motivation for, and nature of, municipal solar policies. Second, we want to understand the causal effects of municipal policies on the adoption of solar photovoltaics. To this end, we adopt a matched difference-in-difference approach, which also takes into account lessons from the recent advances in the microeconometric literature (see Abadie and Spiess, 2021; Baker et al., 2022; Roth et al., 2022).

We find that a significant portion (15.1%) of the municipalities in our sample have one or more of the local solar policies that we study. Overall, we find that municipalities that implement any type of policy have 8.9 percent fewer solar photovoltaic installations and a 10.4 percent smaller solar capacity, effects driven mostly by small to medium-sized installations of 5-10 kW, consistent with the policy goals of shaping the urban built environment. The larger effect on capacity suggests that municipal policies are effective on both the extensive and intensive margins, leading to less adoption as well as smaller installations conditional on adoption.

This paper contributes to several strands of literature. First, an established literature on NIMBYism, including in relation to energy and environmental issues (e.g. Smith and Desvousges, 1986; Frey and Oberholzer-Gee, 1997; Levinson, 1999; Fischel, 2001; Feinerman et al., 2004; Krekel and Zerrahn, 2017). Second, a growing literature on the economics and policy of solar adoption (e.g. Borenstein, 2017; Crago and Chernyakhovskiy, 2017; Gerarden, 2018; De Groote and Verboven, 2019; Gillingham and Tsvetanov, 2019). Third, a broader literature on the role of building codes in the transition towards a greener economy (e.g. Aroonruengsawat et al., 2012; Jacobsen and Kotchen, 2013; Levinson, 2016; Kotchen, 2017). Fourth, a complementary strand of literature analyzing the role of building codes in shaping urban environments and preserving the cultural and historical heritage of towns (e.g. Been et al., 2016; Zhou, 2021).

In terms of policy implications, our paper confirms and quantifies the trade-off between national and global climate mitigation goals and local historical preservation. While our analysis is positive and thus agnostic on whether historical preservation should prime over cost-effectiveness considerations related to the transition to a cleaner economy, we do note that the rapid technological evolution in solar photovoltaic technology has not only led to lower prices for solar panels but also to more options in terms of quality, in particular with respect to how ‘invasive’ solar panels may be. Going forward, such solutions may relax the trade-off that this paper analyzes, making some of the regulations that we cover obsolete or amendable. ‘Invisible’ solar installations could indeed often be compatible with the aesthetics of historical towns, increasing the potential for solar energy wherever a conflict arises between renewable energy goals and local preservation. Making solar ‘invisible’, either through regulations prescribing where solar panels can be located in historical districts or by prescribing the use of photovoltaic roof tiles, may still limit adoption indirectly through peer effects, which the literature finds to depend on an installation's visibility (see Carattini et al., 2019 for a review). Yet, the direct effect of allowing for photovoltaic roof tiles, even if more expensive than conventional solar installations, could already substantially expand solar capacity in historical towns and other areas where similar aesthetic considerations apply.

The remainder of the paper is organized as follows. Section 2. presents the economic and policy background. Section 3. describes our data and methodology. Section 4. discusses the identification strategy and estimation. Section 5. presents our empirical results. Section 6. concludes.

2. Background

As part of the European Union's commitment to the Paris Agreement, Germany strives to become carbon neutral by 2045. Achieving carbon neutrality implies boosting considerably the uptake of renewable energy in the country, as does increasing energy security and reducing reliance on energy imports from third countries. Both energy security and reliance on third countries are issues that are back at the forefront of policymaking in recent times amid renewed geopolitical uncertainty. The primary policy instrument that has been used over the last three decades to promote renewable electricity is a feed-in tariff scheme (FIT) that guarantees a fixed price for renewable energy. Germany first implemented this type of subsidy for electricity production from all renewable energy sources in 1991, as part of the Electricity Feed-in Law, or Stromeinspeisungsgesetz (SEG) (Stromeinspeisungsgesetz, 1990). The SEG required grid operators to purchase electricity produced by solar photovoltaics at a price equalling 90 percent of the average consumer price per kilowatt hour. In 1995, this corresponded to €8 cent/kWh, which did not cover the cost of electricity production from solar photovoltaics (Beste and Kälke, 2013). Hence, in 2000, the Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz" or EEG) replaced the SEG (Erneuerbare-Energien-Gesetz, 2000). Under the EEG, FITs are differentiated by energy source to offset technology-specific cost disadvantages compared to conventional power generation (Böhringer et al., 2017).

Particularly for solar photovoltaics, the EEG dramatically increased feed-in-tariffs compared to the preceding scheme under the SEG. The EEG guarantees producers a fixed above-market price for renewable energy for 20 years from the date of installation. The guaranteed rate for electricity from solar photovoltaics was €50.6 cent/kWh in 2000, and has since dropped to €8.2 cent/kWh in 2020.[1] The EEG prescribed a steady decline in the FIT in anticipation of falling renewable energy generation cost. Any difference between feed-in tariffs paid by the grid operators and the market price is passed on to electricity consumers as a surcharge on the electricity bill. This framework and the structure of the FIT has been retained in a series of revisions of the EEG in 2004, 2009, 2012, 2014, 2017, and 2022. The subsidies fueled the growth in renewable energy production in Germany. The share of renewable energy in gross electricity consumption increased from 3.4% in 1990 to 6.2% in 2000 and to 41.1% in 2021, with solar energy accounting for approximately 20% of all renewable electricity in 2021 (AGEE-Stat, 2022).

The SEG and EEG are federal policies, but lower administrative units -- states, districts, and municipalities -- can alter their impact. Germany has a federal system of government that is shaped by the principle of subsidiarity, which holds that policy issues should be addressed, wherever possible, at the most immediate level. The lowest administrative units are the municipality ("Gemeinde") and collective municipality ("Gemeindeverband"), superseded by districts, governmental districts, and the 16 states ("Länder"). Each state has their own building code that provides a framework for policies at the municipal level. With respect to solar photovoltaics, there are only very minor differences in policy across states. Most importantly, no state requires an application or permit to install solar panels, though municipalities are free to implement regulations beyond the state building code.[2] As of June 2019, there were, for the purpose of this study, 4,691 independent municipalities and 758 collective municipalities.[3] Collective municipalities are a union of at least two municipalities with the purpose of shared governance, administration and policy, with the constituting

[1]This fixed rate has been offered to owners of solar installations with a capacity under 30 kW, with slightly lower rates for higher capacity solar installations.

[2]One exception to this structure are independent cities, which are districts in their own right. Three cities (Berlin, Bremen, and Hamburg) are states in their own right. Hence, they are excluded from our study.

[3]Unless the distinction is critical, we refer to both independent and collective municipalities simply as "municipalities."

municipalities retaining some degree of autonomy. Commonly, collective municipalities are governed by one council and a first mayor. Municipal development, taxes and fees, statutes, ordinances, building codes, and municipal services are typically under the purview of the collective administration, though the degree of integration varies.[4] In sum, both independent and collective municipalities have far-reaching authority to enact building regulations that may affect solar adoption.

In this study, including in the survey to municipalities that we describe in the next section, we distinguish between four types of municipal solar policies: bans, permit requirements, regulations, as well as policies promoting solar adoption. Bans, permit requirements, and other types of regulation are often implemented to preserve the appearance of historical buildings and districts. In our sample, which we describe in the following section, 34% percent of municipalities that implement solar policies are historical towns (see Table 4).[5] The definition of "historical town" stems from a report, which was commissioned by the German Federal Ministry for Transport, Building and Urban Development (Vereinigung der Landesdenkmalpfleger, 2010). In our paper, we follow the categorization provided in the report.

Of the four policy types that we study, bans are straightforward and prohibit homeowners from installing solar panels. Permit requirements are municipal policies that mandate homeowners to either apply for permission to install solar panels or submit building plans to obtain planning permission. Solar regulations cover all other types of policies that municipalities may implement to regulate solar installations. In our study, we request that municipalities explain what their regulation entails. There are three prevalent types of solar regulation that we ask about. These common regulations mandate (1) that solar panels are not visible from the street, (2) do not reflect light on other buildings or the street, and/or (3) that solar panels are integrated in the walls or roof of a building. Finally, we also gather information on the promotion of solar photovoltaics, which refers to municipal-level financial incentives, i.e. tax rebates, for homeowners to install solar panels on existing homes or

[4] In particular, there are four states where the individual municipalities may maintain a greater than usual degree of autonomy: Saxony, Baden-Wurttemberg, Bavaria, and Thuringia. This heterogeneity across states had implications for the distribution of our survey, as discussed in Appendix A.

[5] Nationwide, some 1,900 municipalities (approximately 17 percent) are designated as historical municipalities (Vereinigung der Landesdenkmalpfleger, 2010).

include solar panels in the construction of a new building. As determined by our study, this latter type of municipal policy is relatively rare with respect to the overall penetration of policies limiting the adoption of solar photovoltaics, and is thus not the main focus our study. In sum, bans are the most restrictive solar policy that municipalities can impose, followed by permits and regulations. Across all policies, we distinguish between policies that apply to the entire municipality and policies that only regulate an area, for example, a historical district.

3. Data

3.1. Data sources

We use three sets of data in our analysis. The first dataset is a registry of municipal building policies relating to the adoption of solar photovoltaics, which we created by conducting a survey sent to the building code offices of all municipalities in Germany.[6] To our knowledge, this is the first such registry, worldwide. The second dataset is the Marktstammdatenregister (MaStR), which contains data on the generating capacity of all solar power plants in Germany for the years 1991 to 2019, and is provided by the Federal Energy Agency (Bundesnetzagentur). The third dataset contains socioeconomic characteristics of municipalities and is sourced from the Federal Statistical Office of Germany (Destatis, Statistisches Bundesamt) and the Federal Employment Agency (Bundesagentur für Arbeit).

3.1.1 Building codes

Municipal regulations of solar installations are typically found either in zoning documents (Bauleitpläne) or in statutes (Satzungen). Many municipalities with substantial historical building stocks have dedicated building statutes (Gestaltungssatzungen) intended to regulate and protect historical buildings and the overall appearance of a municipal district. Our registry of municipal solar policies is primarily based on survey responses from municipal officials. In the survey, sent to all municipalities in Germany, we asked about policies that

[6] The survey was complemented with a manual search for all municipalities that did not provide the requested information through the survey, as detailed in Section 3.1.1.

explicitly concern the installation of solar panels, following the classification described in Section 2. We sequentially asked for information on both current and past municipal policies. Municipalities and collective municipalities (as described in Section 2.) received identical surveys, with one exception: collective municipalities could indicate to which constituting municipalities the reported policies apply. To this end, we included an interactive checklist of (sub-)municipalities in the survey sent to collective municipalities. The survey starts with an overview of policies and asks the municipality to indicate which ones are present, based on the options described in Table 1.

As mentioned, the survey asks whether a policy applies to the entire municipality or one or more geographic areas within the municipality. If the policy applies to an area within the municipality we asked to be provided a map, a shapefile with geocoded areas, or a precise description (i.e. cross streets). We also ask that the municipality report the zoning designation (e.g. mixed residential) of the area and whether it is considered an area of historical significance.

The survey was available to municipalities between September 2019 and December 2020. In order to contact all municipalities in Germany, we obtained contact lists from each German state, excluding the three city-states of Berlin, Bremen, and Hamburg. We conducted a small trial in early September 2019, where we sent the survey to 43 independent municipalities, and 23 collective municipalities, allowing us to inspect responses and obtain feedback to make adjustments before scaling up. In October 2019, we started administering the survey to all remaining municipalities. We randomly assigned all municipalities to 1 of 6 waves, and staggered the survey rollout by wave to allow us to provide municipalities with a timely response to questions or to follow up rapidly via email or phone calls in case some fields had been left incomplete. Each municipality received an initial invitation to participate via email (see Appendix Figures A.1 and A.2). The initial invitation was directed, whenever possible, to the building department within the municipality. The email provided a brief introduction to the research project and a link to the online survey. By the end of November 2019, all municipalities had been invited to participate in the survey.

During the remaining months through December 2020, continuing work on the survey primarily consisted of 3 tasks: (1) corresponding with municipal officials who submitted incomplete survey responses, or who reached out with questions about how to complete the survey; (2) obtaining updated contact information to re-send the survey when it was discovered that the state-provided contact lists gave deprecated or inappropriate email addresses; and (3) sending periodic reminders to municipalities which had not yet completed the survey.

In the case of municipalities that opted out of survey participation or never completed the survey, we supplement the dataset with information from publicly available municipal documents. We searched municipalities' websites to collect the same set of information that we required the municipalities to fill in the survey. In order to standardize the data collection as much as possible, we limited the search to certain types of official documents and searched the documents using a pre-defined set of keywords (see Table 2).

In total, we contacted 4,678 independent municipalities and 756 collective municipalities, representing all municipalities in Germany save for a small handful for which we were unable to obtain contact information, and the abovementioned three city states (see Appendix Table A.1 for details by state). The survey response rate is 49.3% among municipalities (2,305 responses) and 32.3% among collective municipalities (244 responses), for an average response rate of 46.9%. Some of the responses are for various reasons not usable, for instance if the respondent failed to provide the start date of a policy, or otherwise left the survey incomplete. As a result, we have 1,102 complete responses for the municipalities, and 103 complete responses for the collective municipalities, implying completion rates of 48% and 42% respectively, and effective response rates of 24% and 14%. To these complete survey responses we add the entries from our manual search process, yielding 172 entries for the municipalities and 26 for the collective municipalities, bringing the total sample to 1,274 and 129, respectively. Notably, the 129 collective municipality responses translate to a higher number of observations in our main dataset, because our unit of observation is the individual constituent municipalities within the collective. Thus, the 129 responses from collective municipalities imply 600 total responses at the municipality level, bringing the total number of municipalities for which we have solar building code data to 1,874.

In Table 3 we present the balance of covariates across survey respondents and municipalities overall. These summary statistics are shown separately for independent and collective municipalities. Collective municipalities are typically smaller than independent municipalities because their constituting municipalities are very small. Overall, municipalities with greater population were more likely to respond to our survey. However, differences between respondents and non-respondents across other observable municipality characteristics are not of meaningful size. Most notably, per capita measures of the number of solar installations added per year and the added annual capacity are not different across survey respondents and non-respondents.

3.1.2 Solar photovoltaics

Our outcomes of interest are the number of solar installations and solar capacity in each municipality and year. In 2019, the federal government made these data on energy market participants available to the public via the MaStR database. The German electricity market has many small producers, including more than 2 million solar installations, implying an overall gross production capacity of 59 GW at the end of 2021. Solar photovoltaics provided 9.1 percent of gross electricity consumption in 2021 (Fraunhofer, Umweltbundesamt, 2022). MaStR was created to provide reliable data on market actors in the energy sector, at a time when the German energy sector was liberalized and the transition to renewable energy was well under way (Bundesnetzagentur, 2018).[7] The MaStR registry contains installation and plant names, name of the owner if not an individual, addresses, type of energy source, and production capacity. Plant owners report the in-service date when the plant installation is completed.[8] All energy market participants are required by law to report any new or existing plant to the Federal Energy Agency and keep this information up to date, regardless of whether they are receiving energy generation subsidies. This rule applies to both conventional and renewable energy generation. The information is verified by the grid operator serving the electricity producer entering the information. Registration of a plant

[7]The Federal Energy Agency (Bundesnetzagentur) provides these data to the public in accordance with the federal code that regulates the energy sector (§ 111e and § 111f of the Energiewirtschaftsgesetz).

[8]MaStR also records a reporting date, which refers to the date that the plant information was entered in the database. New plants need to be registered within one month of the in-service date. Late registration can result in fines and the loss of subsidies. Existing plants that were registered with the Federal Energy Agency prior to the introduction of the MaStR database in 2019 were required to be re-registered with MaStR by the end of January 2021.

is required in order to receive federal subsidies or tax benefits. Failure to register can result in fines. While information about the postal code where the installation or plant is based is public, the street address is not public information for solar plants generating less than 30 kW. Further details about the assignment of solar installations to municipalities are detailed in Appendix B.

3.1.3 Control variables

Our control variables, including demographic and socioeconomic characteristics, are provided by the Federal Statistical Office. These data are provided annually back to 2008, and are tabulated at the level of individual municipalities. In particular, even for municipalities which belong to a collective for administrative purposes and thus receive the collective version of the survey, the control data are still tabulated at the level of the individual municipalities. The specific variables that we include in the analyses are: population, share of males in the population, share of children in the population, the green party vote share, and, at the district level, average household income and unemployment rate.

3.2. Descriptive statistics

Our final dataset is a yearly panel of 1,874 municipalities[9] from 1991 through 2019. This panel includes data on municipal solar building policies, adoption of solar PV, and time-varying socio-economic characteristics of the municipalities. Recall that we distinguish between four types of policies: bans, permits, regulations, and policies that promote solar expansion. In our sample, 294 municipalities have one or more of these policies in place. 153 municipalities regulate the installation of solar panels, 44 require a permit, 22 impose a ban on solar panels, and 33 promote the installation of solar photovoltaics (in addition to existing federal subsidies). Within our dataset, it is necessary to define treatment and control groups based on the solar building policy data that we collected. The treatment group is defined as the 252 municipalities whose treatment status may turn positive sometime between 1991 and

[9]The dataset is defined using the municipality definitions which were current as of 2019, when the survey we used to gather data on municipal solar policies began, as described in Appendix B.

2019. The control group consists of all 1,579 municipalities which never receive treatment.[10]

Figure 1 presents the cumulative adoption of municipal solar building policies in Germany from 1991 through 2019. At each point in time it presents the proportion of municipalities which have implemented solar policies, as a fraction of all municipalities which at some point adopt a policy that we a priori expect to have a negative impact on solar adoption and which are the main focus of this study: bans, permits, and regulations. About 10% of these municipalities report that their policies were in place prior to 1991, and therefore for the purpose of our study do not provide any useful variation in policy. From 1991 through 2019, the adoption of solar policies then occurs at a moderately increasing rate, with only roughly 25% of municipalities treated by 2000, and then nearly 60% treated by 2010.

The boom in solar photovoltaics followed the major increase in the feed-in-tariff rate in the year 2000. We found that 94 municipalities in the sample introduced policies that directly (or indirectly) define rules concerning the installation of solar photovoltaics. Prior to 2000, the average number of solar installations that existed before the implementation of a relevant building code is only 0.17. The average installed capacity is 0.66 kW per year. Hence, these building codes were written at a time when only a handful of solar PVs existed in these municipalities. Typically, pre-2000 building codes explicitly mention solar PVs in passing, for example, alongside antennas and satellite dish regulations. That is, while these building codes impact the adoption of solar photovoltaics, they were not necessarily written with widespread solar adoption in mind.

Since our data on solar installations include a wide range of installations, ranging from small rooftop installations to massive solar fields, it is useful to construct measures of solar adoption that allow us to focus on different categories of installations. In particular, since the urban policies we study should be expected to have implications only for panels within the urban area, we should not expect effects for particularly large installations. To this end, we define outcome variables that separate solar installations into 5 categories, corresponding to the quintiles of the overall gross capacity distribution for all installations

[10]We see that historical towns implemented solar policies at much higher rates than towns without historical districts. In the control group, 12 percent of municipalities are historical towns. In contrast, 34 percent of municipalities that implemented solar policies have historical districts. As described in the following section, the empirical approach takes care of these differences.

from all municipalities and years. Specifically, this procedure results in separate outcomes for PV installations in the capacity ranges of 0-5 kW, 5-7.44 kW, 7.44-10.5 kW, 10.5-22.1 kW, and 22.1 kW and above. Figure 2 shows the cumulative amount of solar capacity installed among each of these separate categories of PV installations from 1991 to 2019, for the 1,874 municipalities in our dataset. From this figure it is evident that while the majority of the 13 GW of capacity installed come from the largest category of installations, there is also a total of 3.7 GW of capacity installed from the 4 smaller categories of installations, and 2.3 GW of capacity from the 3 smallest categories, where we expect the impact of the building policies that we study to be concentrated.

Table 4 provides balances of covariates measuring possible selection across treatment status, using control data for the years 1991 to 1999, prior to any significant installation of solar capacity in the country. From Table 4, we can see that treated municipalities tend to have greater land area, higher population, less installed PV per capita, and are more likely to be a historical town. For this reason, as described in detail in Section 4., we implement a matching approach that significantly reduces the observable differences between treated and control municipalities.

4. Empirical Strategy

4.1. Nearest neighbor matching

Our goal is the estimation of the causal effects of municipal policies on the adoption of solar photovoltaics. We examine the effect of all policies on our outcome of interest and also study separately the impact of regulations and permit requirements, given their frequency in the data.

Municipalities do not randomly implement solar policies. Therefore, the main challenge in the estimation of causal effects stems from the fact that municipalities choose to implement solar policies.

The descriptive statistics in Table 4 tell us that treatment status may in part be correlated with observable municipality characteristics. Hence, to reduce observable differences between municipalities, we use matching as a pre-processing step, followed by regression analysis. More precisely, we implement one-to-many nearest-neighbor matching without replacement. Abadie and Spiess (2021) show that matching as a pre-processing step to estimation yields valid regression standard errors if matching is done without replacement and standard errors are clustered at the level of the match. We follow this approach. The set of matching variables is chosen to produce a comparison municipality that has similar characteristics to a treatment municipality, while maximizing the number of successful matches. For the main estimations, the matching variables are, at the municipality level, population, share of women, share of children, land area, green party vote share, and at the district level, the unemployment rate and household income. In our main specification, we match on the average value of these variables for the years 1991 to 1999. Municipalities in both treatment and control group have some existing solar capacity in the late 1990s. However, the timeframe is chosen such that the positive effect of the 2000 renewable energy legislation on solar adoption does not play a role. As we can see in Figure 2, almost all the solar capacity installation occurred after the year 2000. Approximately one third of municipalities in the main estimation sample implemented solar policies prior to 2000, suggesting that in those cases, the policy decision was not driven by existing solar capacity.

As we can see in Table 4, matching reduces observable differences between treated and control municipalities but does not completely eliminate them—though an exact match is not a necessary condition for identification.

To evaluate the robustness of the matching strategy, we implement a number of alternative specifications. First, we restrict our sample to the years 2000 to 2019 to focus on a period of significant solar expansion. Here we match not only on the 2000 values of the covariates but on the level of solar capacity installed prior to treatment. Second, we also consider a municipality's status as a historical town, fixed over time, as an additional matching variable. Third, we create analysis samples using one-to-one nearest neighbor matching, which mechanically implies a smaller sample size. Fourth, we match municipalities within the same state only. Fifth, we provide analyses removing any combination of two states at the time, to show that our results are not driven by one state in particular, or two states in particular.

Finally, in the estimation of our main specification, we treat the introduction of a municipal solar policy as a canonical binary effect, estimated for all policies and for separate types of policies. Some municipalities have solar policies that apply only to a subset of the total land area of the municipality. Hence, as a robustness test, we include an additional set of estimations where we account for area-specific policies using a continuous variable (see Section 5.3.).

4.2. Main empirical specification

Once we obtain the matched sample, we use a two-way fixed effects estimator to identify the average treatment effect on the treated (ATET) of municipal solar policies on installed solar capacity. Since municipalities implement solar policies in staggered fashion, our analysis departs from the canonical difference-in-difference design. Roth et al. (2022), in a review of the recent difference-in-difference literature, show that a standard two-way fixed effects approach yields the ATET of a staggered policy if the treatment effect is homogenous and not dynamic. We account for these insights in two ways. First, by relying on one of the recent estimators covered in Roth et al. (2022), as described below. Second, to assuage potential concerns that when using a two-way fixed effects estimator our estimate may be biased due to treatment effect heterogeneity, we separately analyze different types of policies, and quintiles of solar capacity. Hence, we estimate regression equations of the form:

$$Y_{it} = \beta * Treated_{it} + \gamma Z_{it} + \alpha_i + \alpha_t + \epsilon_{it} \tag{1}$$

Where $Treated_{it}$ is a binary variable indicating whether a given municipality i has adopted the policy under consideration. Y_{it} is one of twelve outcome variables measuring the yearly flow of new solar in a municipality, with one outcome variable for the total, and one variable for each of the five quintiles defined in Section 3.2., measured in either (natural) log of the number of installations or log of total gross capacity installed.[11] Z_{it} is a vector of time-

[11]Note that to retain in the estimation sample the municipality-year observations that have zero solar photovoltaic installations (and thus capacity as well), we define our outcome as log(1+x). We confirm the robustness of this transformation by re-estimating the main model using the inverse hyperbolic sine (IHS) transform of capacity and installations as outcome variable for all our main estimations. Estimates are robust also for the remaining robustness tests and alternative specifications.

varying control variables that mirrors the covariates used in the matching procedure: (log) population, the share of males in the population, the share of children in the population, the share of green party voters, household income, and the unemployment rate. The α's are municipality and year fixed effects, and ϵ is an error term.

Any generalized difference-in-difference approach requires careful discussion of the parallel trend assumption. In our case, we assume that the newly installed (log) solar capacity (or total number of installations) in treated municipalities would have followed the same trajectory (in the absence of solar policies) as newly installed (log) solar capacity (or total number of installations) in control municipalities. The parallel trend assumption tends to be sensitive to the functional form of the estimated model (Roth and Sant'Anna, 2022). We choose the (natural) log of capacity and log of installations as our outcome variables because in the absence of a solar policy it is plausible that solar capacity in a treated municipality would have increased by a constant proportion.

In our main specifications, we assume that the parallel trend assumption holds conditional on matching and covariates. We conduct a series of event studies, following Borusyak et al. (2021), with the dual goal of analyzing pre-trends and measuring the impact of solar policies on the outcomes of interest using an estimator that fits heterogeneity and dynamic effects in staggered implementation. As described in detail in the following section, we estimate the event studies on both the entire analysis sample, as well as the matched sample, and in both cases reject the presence of significant pre-trends. Further, in one event study analysis, we impose the parallel trend assumption without conditioning on covariates. Testing the parallel trend hypothesis allows us to also account for potential anticipatory effects, potentially leading homeowners in regulated towns to adopt solar just prior to the regulation's entry into force.

5. Empirical results

5.1. Main regressions

Tables 5 and 6 present the main results of estimating a number of regression equations of the form specified in Section 4., equation 1; each cell of these tables provides a different estimate $\hat{\beta}$ from a different specification estimated on data from 1991 through 2019. Table 5 shows the treatment effect estimates for all solar policies. Table 6 shows the treatment effect estimates for permits and regulations. The rows of each table correspond to different outcome variables, so the first row presents results based on the total capacity installed per year, followed by the smallest solar installations (<5 kW) and the bottom row presents results on the largest installations (>22.1 kW). The first column shows the results for (log) capacity, the second column shows the results for the (log) number of installations.

$\hat{\beta}$ should be understood as the average difference between observed solar installations (or capacity) per year in a municipality which has adopted a given policy, and a counterfactual estimate of the solar installations the municipality would have seen if it had not adopted the policy. The counterfactual is informed by the national time trend in solar adoption (year fixed effects), translated up or down to match the overall level of solar adoption in the municipality (municipality fixed effect), and allowed to accommodate differential trends across municipalities based on evolution in the municipality's demographic and economic characteristics (time-varying controls).

In Table 5 we see that solar photovoltaic policies reduce the number of installations and solar photovoltaic capacity. Overall, municipal solar policies reduce the number of installations by 8.9 percent and reduce capacity by 10.4 percent. That is, we find a larger effect on capacity than on installations, pointing to the ability of municipal policies to influence both the extensive and intensive margins, leading to fewer installations as well as smaller installations conditional on adoption. We confirm that the difference in coefficients between installations and capacity is statistically significant at conventional levels for all quintiles except the top two quintiles.

The policy effect on the number of installations is smaller for higher capacity solar photovoltaics. The reduction in capacity is most pronounced, and precisely estimated, for installations between the 20th and 60th percentile of capacity. This corresponds to installations between 5.0 kW and 10.5 kW of capacity, a typical size for single family rooftop solar photovoltaics. It makes also sense that the quintile with the smallest installations may be less affected, as small installations generally tend to be less invasive.

In Table 6 we see that the overall effect of the most common types of policies, regulations and permit requirements, reduce capacity by 18.5 percent and the number of installations by 16.3 percent. For these two most common types of policy we also see the largest reduction for installations between the 20th and 60th percentile of capacity. Once more, we see that both the extensive and intensive margins are affected, with the coefficients for capacity being larger than the coefficients for installations, significantly so in several cases, confirming the pattern at which Table 5 hinted.

In order to interpret these results at the aggregate level, it is useful to begin by considering the aggregate impact among all municipalities in our sample. One simple way to estimate this impact is to calculate the total amount of solar capacity installed in treatment municipalities during treatment years, and then multiply it by the obtained regression coefficients. For simplicity, in the following calculations we consider only the effects for the 3 bottom quintiles of the capacity distribution, since this is where we find most action to take place. The total amount of solar capacity for all treatment years within treated municipalities is 54 MW for the smallest installations, 91 MW for the next capacity class, and 154 MW for the middle quintile. Multiplying by the Table 5 coefficients of 9.0%, 14.1%, and 16.6%, respectively, the estimated impact of solar policies on solar adoption in each size class is 5 MW, 13 MW, and 26 MW, for a total of 44 MW. The total amount of solar capacity installed among the municipalities in our sample over the entire period is 2,276 MW, so the aggregate impact is about a 2% effect. Extrapolating to the national level, a 2% effect would represent a loss of 160 MW of solar, as there is a total of 7,500 MW of installed capacity among the three size categories throughout Germany.

In these calculations, we only focus on overall solar capacity. That is, when deriving policy implications, we assume that every solar installation counts the same. This is likely to be largely the case as in the European context the development of the electricity grid is relatively advanced. Recall that the goal of our study, in general, is to illustrate and quantify the trade-off between national (and global) goals of energy security and climate change mitigation and local goals of preservation. If, following our study, municipalities would reconsider their policies and subject them to a more careful analysis of costs and benefits, acknowledging that not all benefits may accrue locally, we do consider important for them to also account for municipality-specific features with respect to grid congestion and connectedness. They could do so building on a growing literature in this area (e.g. Fell et al., 2021; Gonzales et al., 2022 for related studies), although we expect these features to be largely similar across municipalities for most contexts.

5.2. Event study

In this section, we present the results of our event study, which follows the methodology described in Section 4. Figures C.37 to C.54 display the main results from this exercise. First, we look at the ex-ante period and confirm that there is no evidence of significant pre-trends, which supports the analyses presented in this section.

Then, we discuss how the event study replicates our main results, as presented above, as well as the timing of treatment effects, which event studies allow us to measure. Generally speaking, the event analyses replicate our main results well, with larger effects for permits and regulations, which are, as mentioned, the most popular policies in our sample, and somewhat smaller effects when all municipal policies are taken together.

As expected, the results are particularly clear for installations at or below the 60$^{\text{th}}$ percentile of capacity. In terms of timing, the effects grow in magnitude over time, and after 5 years we see annual reductions in the range of 10 to 15 percent for the smaller installations, as shown in Figures C.38 and C.39 for installations and Figures C.44 and C.45 for capacity.

5.3. Additional robustness tests

In this section, we present the results of a battery of robustness tests around our main results, as reported in Tables 5 and 6.

In Table D.1 we present the estimation results of a modified version of equation 1, with

$Treated_{i,t}$ redefined as a treatment intensity measure. We see in Table D.1 that increasing the urban area covered by regulations and permit requirements by 10% reduces capacity by 3.6% and the number of installations by 2.5%.

Tables D.3 to D.6 display our main estimates when using the inverse hyperbolic sine transformed outcome. Estimates for each quintile are generally robust to this transformation and, most of the time, slightly larger than in our main specifications. The pattern observed above for the intensive and extensive margin also generally holds for each quintile, except for the largest quintiles, although not for the average over all quintiles.

In Table D.7 we show that the coefficient estimates from the restricted sample that starts in the year 2000, when the feed-in-tariff subsidies were increased, closely match the main results. The results are also robust to exact matching on the historical status of a municipality (see Table D.8), and exact matching of municipalities within a state (see Table D.9). In the latter case, we note that, if anything, estimates point to larger effects.

In another robustness test, we remove the states of Baden-Württemberg and Bavaria from our sample. These 2 Southern states account for 43% of the 13 GW of total solar capacity in our sample. Similarly, they account for 50% of all municipalities in the treatment group. While feed-in tariffs are constant across the country, Southern states generally benefit from more sunlight. It is therefore reasonable to be concerned about our results being potentially driven by municipal policies in these 2 states. Table D.10 presents the results of these regressions. Despite the smaller sample, the effect of municipal policies is larger and more precisely estimated in the Northern parts of Germany, for instance in the case of installations pointing to a higher fraction of marginal adopters.

As a further extension of the above exercise, Figure D.1 displays the range of estimates obtained for the effect of solar policies on adoption of the smallest installations over 78 different permutations of the estimation sample. In each permutation, 2 states are removed from the estimation sample, so that we assess the robustness of our findings not only to the removal of 2 particular large Southern states, but to all states in the data. With a total of 13 states, there are 78 possible combinations of 2 states to remove. The resulting point estimates of the effect are tightly clustered around an average of -0.17, with the smallest effect size being approximately -0.1, consistent with our baseline results.

Finally, Table D.11 and Table D.12 present results using a different strategy for the matching pre-processing step, as mentioned in Section 4.1. Here we implement one-to-one nearest neighbor matching without replacement. The results obtained with this different matching strategy are very similar to the main results, once again providing robustness to our main findings.

6. Conclusions

Since the 1990s, subsidies to renewable energy, and to solar PV in particular, have been effective in promoting the adoption of new energy sources and spurring innovation in the renewable sector. However, at the very same time, local policies might have counteracted the adoption of solar energy. As we assess in this paper, a substantial share of German municipalities have over time amended their building codes to place restrictions on the adoption of solar PV, often with the aim of preserving the historical aesthetic of the town. With the cumulative innovation and economies of scale that have been achieved in solar PV energy over the past three decades resulting in grid parity, large subsidy programs are being gradually discontinued, making remaining non-pecuniary barriers to solar PV adoption an important topic for empirical research and policymaking.

We document the spread of municipal policies that restrict the adoption of solar PV by means of administering a survey regarding such policies to all German municipalities. Additionally, our survey distinguishes between several varieties of policies which are adopted by municipalities, and we find that while outright bans of solar PV are relatively rare, there are a larger share of municipalities which require residents to go through a permitting process before installing solar, and a still larger share that regulate the precise manner in which solar can be installed, for instance requiring that they be installed on a portion of the roof such that they not be visible from the street.

We also combine these data on policies with comprehensive data on all solar installations connected to the German power grid, to assess the degree to which municipalities that adopt these policies see a reduced rate of solar adoption, both in terms of aver of installations and their size. Using several empirical strategies, we find that these solar policies affect both the intensive and extensive margins of adoption, leading to an aggregate reduction of approximately 160 MW of installed solar capacity at the national level, or approximately 2% of the 7,500 MW of capacity installed nationally in the three quantiles of the capacity distribution in which we find an effect of the policies.

We shed light on this trade-off between local and national (and even global) goals, a so far under-explored case of NIMBYism with very important implications as countries strive to accelerate their transition towards a cleaner economy as well as to minimize their dependence on imports of energy from foreign countries at a time of renewed geopolitical uncertainty, potentially highlighting the need for additional scrutiny on some of the policies that we study, in Germany as elsewhere, accounting also for the evolution in the solar PV technology.

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Tables

Table 1: Municipal solar policies considered in the survey

Type	Policy	Coverage
Building codes	Ban on solar PV	
		In the entire municipality
		In a part of the municipality
	Regulation of solar PV	
	Street visibility	In the entire municipality
		In a part of the municipality
	Light reflection	In the entire municipality
		In a part of the municipality
	Wall/roof integration	In the entire municipality
		In a part of the municipality
	Solar PV is promoted by the municipality	
		In the entire municipality
		In a part of the municipality
Permits	Specific permits for solar PV	
		In the entire municipality
		In a part of the municipality

Table 2: Keywords for manual search of policies

Search Term	Translation
Bauordnung	Building code
Bausatzung	Building statutes
Bauleitplan	Zoning plan
Gestaltungssatzung	Design statutes
Gestaltungsrichtlinie	Design guidelines
Gestaltungsleitfaden	Design guidelines
Baugestaltungsordnung	Building design code
Stadtbildsatzung	Cityscape statutes
Ortsgestaltungssatzung	(place) Design statutes
Abstandsflaechensatzung	Clearance area statutes
Aussenbereichssatzung	Outskirt / exterior statutes

Table 3: Municipality Characteristics: All vs. Surveyed (1991-1999 Avg.)

	Collective Municipalities			Indep. Municipalities		
	All Mean/SD	Survey Mean/SD	Diff.	All Mean/SD	Survey Mean/SD	Diff.
Municipal Population	1,169	2,048	-879.21***	9,235	22,045	-12810.50***
	(1,580)	(2,244)	(-14.57)	(19,840)	(60,837)	(-10.36)
Share of Males	0.50	0.50	-0.00**	0.49	0.49	0.00*
	(0.02)	(0.02)	(-2.70)	(0.01)	(0.01)	(2.33)
Pop. Share of Children	0.07	0.10	-0.02***	0.07	0.08	-0.00*
	(0.04)	(0.06)	(-15.68)	(0.03)	(0.04)	(-2.11)
Unemployed Rate	0.03	0.02	0.00***	0.02	0.02	0.00
	(0.02)	(0.01)	(3.34)	(0.01)	(0.01)	(1.58)
Green Party Vote Share	0.05	0.05	-0.00	0.06	0.06	-0.00***
	(0.03)	(0.02)	(-0.53)	(0.03)	(0.03)	(-6.55)
PV Capacity (KW)	0.04	0.05	-0.01	0.33	1.18	-0.85***
	(0.44)	(0.22)	(-0.62)	(2.92)	(8.29)	(-4.96)
No. of PV Installations	0.01	0.02	-0.01**	0.08	0.30	-0.22***
	(0.05)	(0.08)	(-2.87)	(0.42)	(1.78)	(-6.35)
Installed KW's per km^2	0.00	0.00	-0.00	0.01	0.02	-0.01***
	(0.01)	(0.02)	(-0.96)	(0.05)	(0.06)	(-4.46)
Solar Installations per km^2	0.00	0.00	-0.00	0.00	0.00	-0.00***
	(0.00)	(0.01)	(-0.92)	(0.01)	(0.02)	(-6.41)
Installed KW's per 1000 Pop.	0.01	0.01	0.00	0.01	0.01	-0.00
	(0.05)	(0.06)	(0.23)	(0.04)	(0.03)	(-0.69)
Solar Installations per 1000 Pop.	0.00	0.00	0.00	0.00	0.00	-0.00
	(0.02)	(0.02)	(0.58)	(0.01)	(0.01)	(-1.75)
N	4,997	948	5,945	2,821	1,832	4,653

Note: The no. of obs. in the "Collective Municipalities" columns reflects the no. of constituent municipalities.

Table 4: Municipality characteristics (averages over 1991-1999): unmatched vs. matched Set

	All			Matched		
	Control Mean (SD)	Treated Mean (SD)	Pre-Match Diff.	Control Mean (SD)	Treated Mean (SD)	Post-Match Diff.
Municipal population	12,416	23,493	-11076.89***	10,870	13,295	-2,425.00
	(36,845)	(88,967)	(-3.44)	(13,131)	(16,383)	(-1.71)
Share of males	0.50	0.49	0.00**	0.50	0.50	0.00
	(0.01)	(0.01)	(3.18)	(0.01)	(0.01)	(0.30)
Share of children	0.07	0.06	0.01***	0.06	0.06	0.00
	(0.03)	(0.02)	(3.51)	(0.02)	(0.02)	(0.16)
Unemployment rate	0.05	0.05	-0.00*	0.05	0.05	-0.00
	(0.02)	(0.02)	(-2.41)	(0.03)	(0.03)	(-0.08)
Household income	21,284.59	21,319.68	-35.09	21,240.96	21,217.67	23.30
	(3,820.34)	(4,504.94)	(-0.13)	(4,423.37)	(4,364.38)	(0.06)
Green Party vote share	0.06	0.07	-0.01***	0.06	0.06	-0.00
	(0.03)	(0.03)	(-3.84)	(0.03)	(0.03)	(-0.41)
Historical municipality	0.12	0.34	-0.22***	0.17	0.32	-0.16***
	(0.32)	(0.48)	(-9.48)	(0.38)	(0.47)	(-3.82)
PV capacity (KW)	234.05	292.62	-58.57*	249.93	267.21	-17.28
	(324.65)	(410.09)	(-2.56)	(298.83)	(357.74)	(-0.55)
PV installations	9.73	13.30	-3.57***	10.67	11.51	-0.84
	(11.52)	(18.51)	(-4.14)	(10.93)	(11.66)	(-0.78)
Installed KW per km^2	5.64	5.76	-0.12	5.87	6.01	-0.14
	(6.51)	(6.26)	(-0.26)	(6.25)	(6.50)	(-0.22)
Solar installations per km^2	0.26	0.28	-0.02	0.27	0.29	-0.01
	(0.21)	(0.23)	(-1.51)	(0.22)	(0.22)	(-0.60)
Installed KW per 1000 inhabitants	40.84	39.88	0.97	36.94	42.93	-5.99
	(63.52)	(120.64)	(0.19)	(59.90)	(128.89)	(-0.62)
Solar installations per 1000 inhabitants	1.58	1.34	0.24**	1.46	1.39	0.06
	(1.33)	(1.20)	(2.65)	(1.27)	(1.21)	(0.53)
N	1,579	252	1,831	219	219	438

Table 5: Effect of any policy on solar adoption

	(1) Log Capacity	(2) Log Installs
All installations	-0.104	-0.0892
	(0.0965)	(0.0580)
1^{st} quintile	-0.0897	-0.0529
	(0.0602)	(0.0403)
2^{nd} quintile	-0.141*	-0.0829*
	(0.0755)	(0.0471)
3^{rd} quintile	-0.166**	-0.0867*
	(0.0830)	(0.0489)
4^{th} quintile	-0.131	-0.0640
	(0.0829)	(0.0400)
5^{th} quintile	-0.129	-0.0621
	(0.126)	(0.0452)
Time-varying controls	Yes	Yes
N	33169	33169
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.616	0.642
Adj. within R^2	0.00514	0.00848

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table 6: Effect of permits & regulations on solar adoption

	(1) Log Capacity	(2) Log Installs
All installations	-0.185*	-0.163**
	(0.110)	(0.0643)
1st quintile	-0.157**	-0.105**
	(0.0654)	(0.0435)
2nd quintile	-0.219***	-0.133***
	(0.0831)	(0.0505)
3rd quintile	-0.266***	-0.143***
	(0.0899)	(0.0508)
4th quintile	-0.251***	-0.124***
	(0.0918)	(0.0416)
5th quintile	-0.164	-0.0789*
	(0.134)	(0.0459)
Time-varying controls	Yes	Yes
N	43721	43721
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.623	0.651
Adj. within R^2	0.00996	0.0129

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Figures

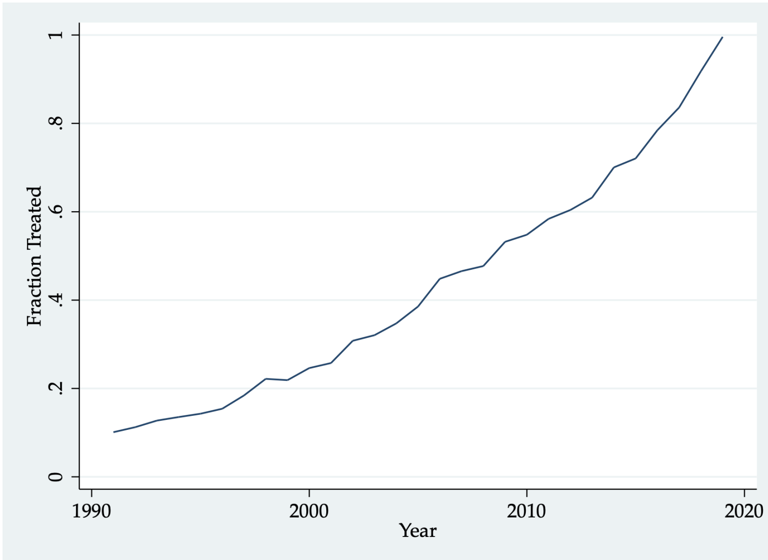


Figure 1: Cumulative share of municipalities that have solar policies

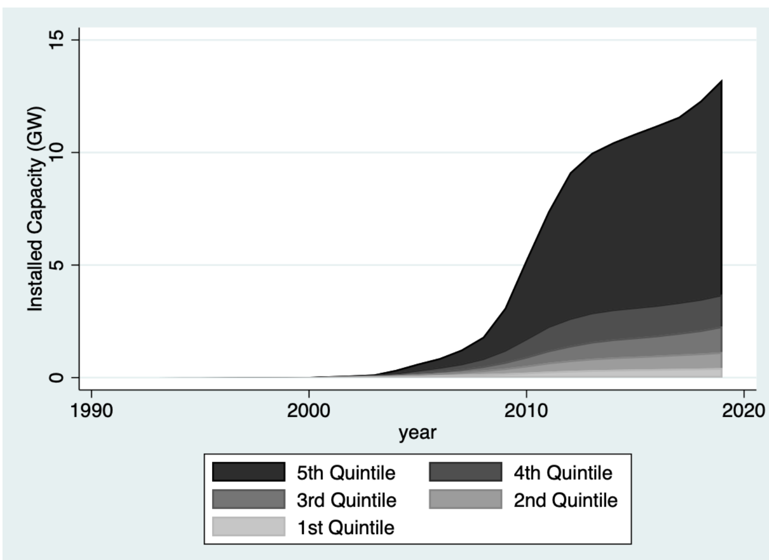


Figure 2: Evolution of solar capacity

A Survey distribution and sampling

The purpose of this Appendix section is to provide a detailed account of how our survey was distributed. Within Germany's federal system of government, the the low level units of local government which are relevant for our study are the Gemeinde and Gemeindeverband, which we generally refer to in the main text as municipalities and collective municipalities, respectively. The registry of local governments maintained by the federal government organizes the units of government with a numbering system known as Amtlichen Regionalschlüssel, or ARS for short.[12] In this system, Gemeindeverband are indicated by 9-digit codes, and individual Gemeinde by 12-digit codes, where the constituent Gemeinde within a Gemeindeverband will share the first 9 digits of their code, distinguished only by the final 3 digits.

As mentioned in the main body of text, Gemeindeverband are often formed for the purpose of centralizing administrative functions for a group of (small) towns. However, the meaning of the term Gemeindeverband varies across states, which have different traditions. Therefore, it is not strictly the case that in every instance where the federal government's registry shows that a Gemeindeverband exists, that the constituent Gemeinde retain no administrative capacity whatsoever. In particular, there are 4 Southern states where this is not the case: Baden-Württemberg, Bavaria, Saxony, and Thuringia. For the states of Baden-Württemberg and Saxony, all municipalities belonging to a collective retain enough of their own administrative capacity that for the purposes of this study, the individual municipalities were the appropriate bodies to reach out to with our survey.

Further exceptions are present in the states of Bavaria and Thuringia, though they are less uniform. In Bavaria, out of 982 municipalities within 311 Gemeindeverband, the majority do not retain their own functions, and so we reach out only to the Gemeindeverband office. However, 405 of those municipalities across 126 Gemeindeverband do retain their own offices, in the manner of Baden-Wurttemberg and Saxony, and so we reach out to the individual municipalities. In Thuringia, the vast majority of the 559 municipalities within Gemeindeverband do not retain their own functions, with 6 exceptions. The city

[12] This system is similar to the FIPS codes used in US Census data, with the first 2 digits of each code indicating state membership, and subsequent digits indicating region, district, Gemeindeverband, and finally Gemeinde membership.

of Saaleplatte in the county Weimarer Land is representative of these exceptions; it is a city of 2,862 people, in a Gemeindeverband anchored by the city of Bad Sulza, which has 4,819 people. The other 6 towns in the Gemeindeverband have populations of less than 800 people, so the secondary city of Saaleplatte retains its own administrative function, while the Gemeindeverband deals with the principal city and surrounding small towns.

Table A.1 provides a detailed breakdown by state of the independent and collective municipalities and how they were categorized for the purpose of this study. Figures A.1 and A.2 display the email which was sent to municipalities to invite them to participate in the survey.

Table A.1: Survey distribution, by state

State	(1)	(2)	(3)	(4)	(5)
Schleswig-Holstein	86	1020	84	86 (4)	84 (2)
Lower Saxony	292	653	116	292 (1)	116
North Rhine Westphalia	396	0	0	396	0
Hesse	423	0	0	423	0
Rhineland-Palatinate	42	2262	139	42	139
Baden-Württemberg	190	911 (911)	270	1,101 (3)	0
Bavaria	1,074	982 (405)	311	1,479	185
Saarland	52	0	0	52	0
Brandenburg	146	271	52	146	52
Mecklenburg	40	686	76	40 (1)	76
Saxony	238	181 (181)	71	419 (3)	0
Saxony-Anhalt	104	114	18	104	18
Thuringia	105	559 (6)	88	111 (1)	88
Germany (sans Berlin, Bremen, and Hamburg)	3,188	7,639 (1,503)	1,225	4,691 (13)	758 (2)

(1) 12-digit ARS codes not belonging to a Gemeindeverband; (2) number of municipalities that do belong to a Gemeindeverband, and in parentheses the number that are, for the purpose of this study, treated as independent; (3) number of Gemeindeverband (9-digit ARS codes); (4) number of effectively independent municipalities, which is the sum of the first column and the parenthetical values of the second column, and in parentheses the number for which contact information could not be gathered; (5) the number of effective Gemeindeverband, which is the value of the third column less those whose constituent municipalities are all treated as independent municipalities, and in parentheses again the number for which contact information could not be gathered.

Sehr geehrte Damen und Herren,

Wir sind eine Forschergruppe von der Universität Münster und der Georgia State University in den U.S.A. Im Rahmen eines wissenschaftlichen Forschungsprojektes, erstellen wir eine Datenbank von Bauvorschriften auf Ebene der Gemeinden, welche die Anbringung von Photovoltaikanlagen betreffen.

Der Lehrstuhl für Mikroökonomik an der Universität Münster lädt ihre Gemeinde ein, so wie alle Gemeinden in Deutschland, den folgenden Online Fragebogen zu beantworten: LINK.

Die Erforschung der Akzeptanz und Verbreitung von Photovoltaikanlage ist wichtig in Zeiten des Klimawandels und der stetigen Vergünstigung von Solarenergie. Durch ihre Teilnahme helfen sie uns bereits öffentlich zugängliche Daten systematisch zu sammeln und schaffen damit die Voraussetzung für unsere Forschungsarbeit.

Ihre Teilnahme an der Umfrage ist freiwillig. Wir hoffen das ihre Gemeinde die Zeit zur Beantwortung des Fragebogens, circa 10-15 Minuten—je nach Anzahl der relevanten Bauvorschriften in ihrer Gemeinde—zur Verfügung stellen möchte.

Wenn Sie nicht alle notwendigen Informationen zur Verfügung haben, um den Fragebogen auszufüllen, bitten wir sie diesen Link an eine andere Person in Ihrer Verwaltung weiterzuleiten. Sie können den Fragebogen kurz ausfüllen oder sich etwas mehr Zeit nehmen, um zusätzliche Details in den Bemerkungsfeldern anzugeben. Sie haben die Möglichkeit den Fragebogen abzubrechen und später an die gleiche Stelle zurückzukommen.

Falls Sie Fragen haben oder uns die Informationen direkt mitteilen möchten, können Sie uns unter +49 XXX XXX XXX anrufen oder sich per Email an uns wenden: sonnenenergie@wiwi.uni-muenster.de für weitere Fragen stehen wir Ihnen gerne zur Verfügung!

Wir danken Ihnen für Ihre Aufmerksamkeit, zählen auf Ihre Teilnahme und verbleiben,

Mit freundlichen Grüssen

Das Projektteam
Prof. Dr. Andreas Löschel, Universität Münster
Dr. Stefano Carattini
Herr Béla Figge
Herr Alexander Gordan

Figure A.1: Survey invitation letter (original)

Dear Sir or Madam,

We are a research team at the University of Muenster and Georgia State University in the United States. As part of a scientific research project we are creating a database of building codes at the municipal level insofar as they concern the installation of solar panels.

The Chair of Microeconomics at the University of Muenster is inviting your municipality, and all other municipalities in Germany, to fill out this survey: LINK.

As solar energy becomes cheaper, and mitigating climate change becomes more urgent, identifying potential ways to scale up the adoption of solar energy is crucial. By responding to this survey, you are helping us to systematically collect data that is already publicly available. Your response makes our research project possible.

Participation is voluntary. We hope that your municipality can take the time – around 10-15 minutes – depending on the number of regulations implemented in your municipality.

If you do not have all necessary information at hand to answer the survey, please forward this link to another individual in your administration. You can answer this survey quickly or take a bit more time to leave additional comments. You will be able to pause the survey and return to the same question at a later time.

If you have questions or would like to provide the information directly to us, you can call us at +49 XXX – XXX – XXX or contact us via at email at: sonnenenergie@wiwi.uni-muenster.de. We are happy to answer any questions you may have!

Thank you for taking the time to participate.

Best regards,
The Research Team
Prof. Dr. Andreas Loeschel, University Muenster
Dr. Stefano Carattini
Herr Béla Figge
Herr Alexander Gordan

Figure A.2: Survey invitation letter (English translation)

B Building the dataset

This section describes how we built our main dataset, covering both the inclusion of data on solar installations and the definition of German municipalities over time.

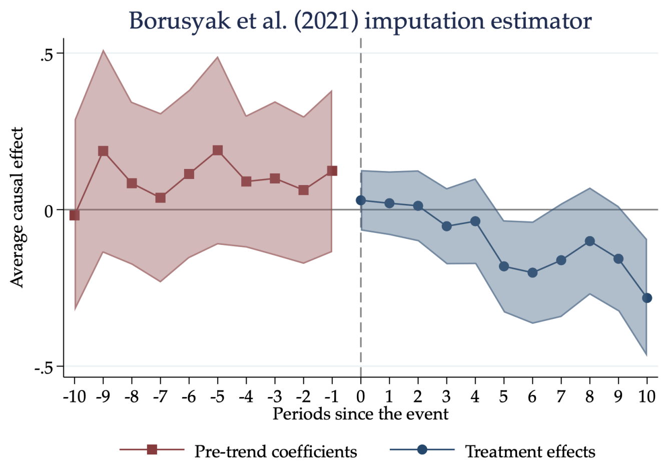
We start with the data on solar installations. As mentioned in the main body of paper, our analyses rely on the MaStR database for information about solar installations at the municipal level. However, we note here that for the purpose of confidently matching the solar data to the information that we collected from municipalities on solar policies and control data, we also rely on the predecessor of the MaStR database, the Erneuerbare-Energien-Gesetz (EEG) database. While the EEG database only covers installations from before 2016, it does include in its public version information on exact addresses of all solar installations, and not only the largest ones as it is the case for the MaStR database. Exact addresses can be easily converted to latitude and longitude using a geocoding service offered by the German government and improve the reliability of the match with the other data used in the analyses. Since the shapefiles use the same registry of municipalities that we used to construct the mailing list for the survey on solar policies, this strategy ensures proper matching between data sources. Furthermore, since municipality definitions can change over time, using a single registry ensures that a fixed set of municipality definitions are used throughout the analysis, which are separately described in the following section.

Then, we describe how we approach the structure of municipalities in Germany over time. The municipality definitions used throughout the text are the definitions which were current as of June 2019, when the survey was first being designed and fielded. However, municipality definitions are not fixed over time, since municipalities sometimes go through administrative mergers or separations. In order to conduct our panel data investigation, which brings together data on solar installations, municipal policies, and demographic information, all covering multiple decades, we need to use a consistent set of municipality definitions over time. We are able to do this by making use of the full record of changes in municipality definitions and mergers over time since 2007, provided by the Federal government. Although some records on municipal mergers prior to 2007 are available, some going as far back as 1980, prior to re-unification, these records are spottier and so we focus attention on the comprehensive records which are available starting from 2007.

C Event study

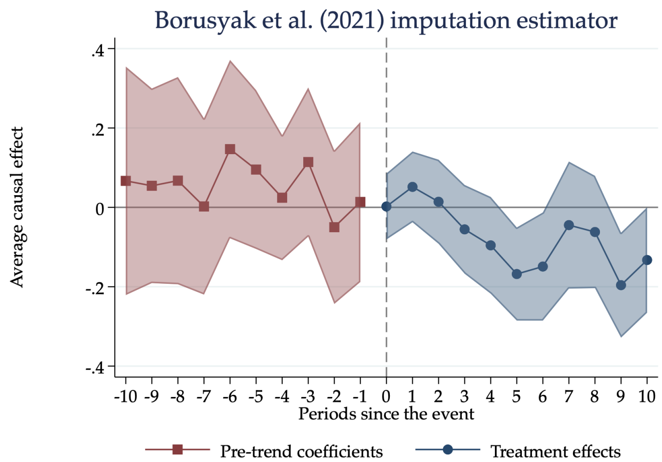
C.1 Unmatched Sample: All Solar Policies

Figure C.1: Event analysis: Effect of all solar policies on (log) installations



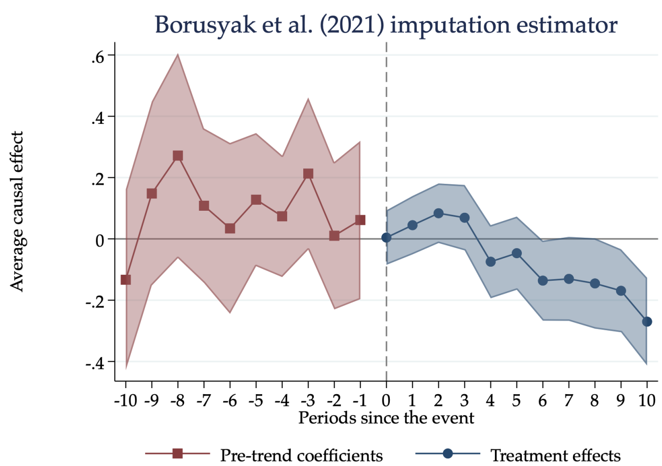
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.2: Event analysis: Effect of all solar policies on (log) installations below the 20$^{\text{th}}$ percentile of capacity



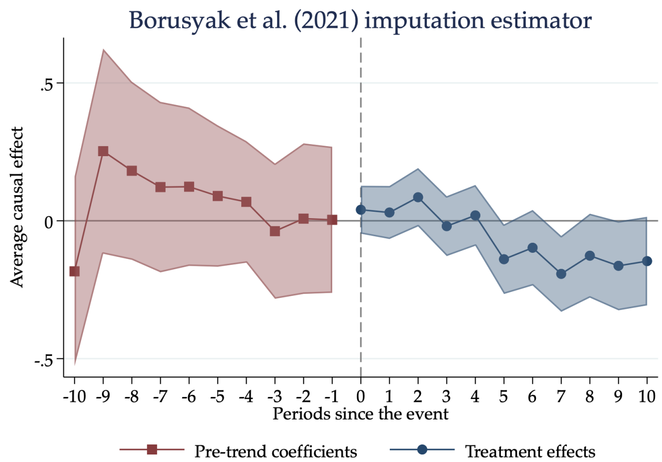
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.3: Event analysis: Effect of all solar policies on (log) installations at 20$^{\text{th}}$ to 40$^{\text{th}}$ percentile of capacity



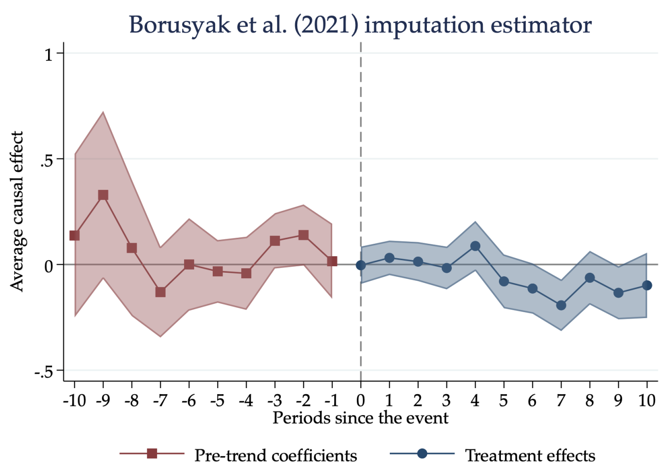
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.4: Event analysis: Effect of all solar policies on (log) installations at 40^{th} to 60^{th} percentile of capacity



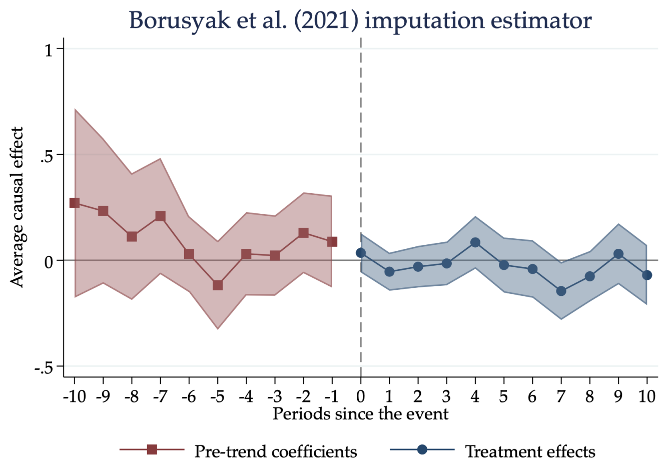
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.5: Event analysis: Effect of all solar policies on (log) installations at 60^{th} to 80^{th} percentile of capacity



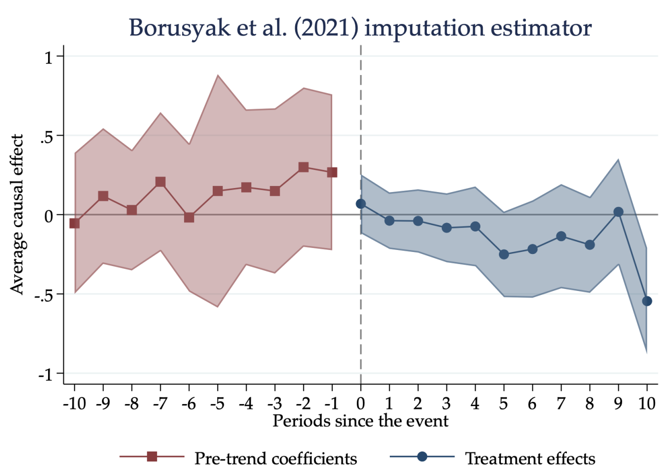
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.6: Event analysis: Effect of all solar policies on (log) installations above the 80th percentile of capacity



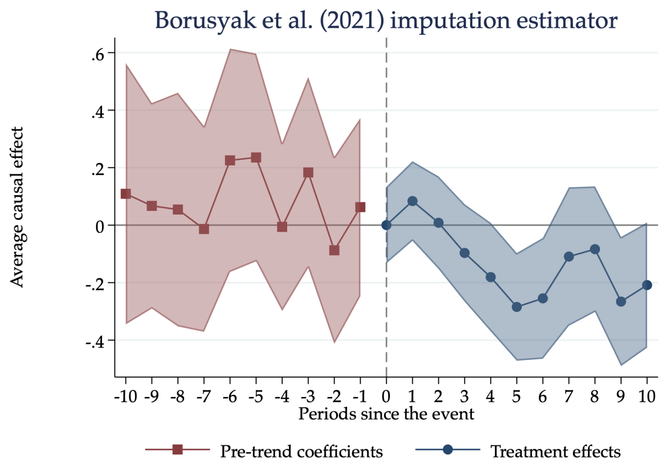
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.7: Event analysis: Effect of all solar policies on (log) capacity



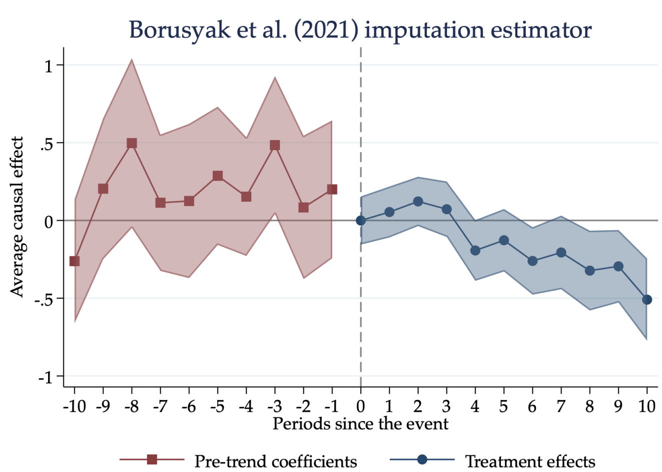
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.8: Event analysis: Effect of all solar policies on (log) capacity below the 20th percentile of capacity



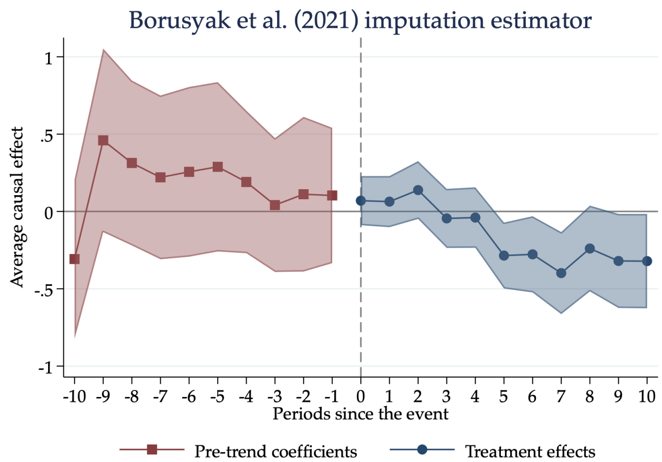
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.9: Event analysis: Effect of all solar policies on (log) capacity at 20th to 40th percentile of capacity



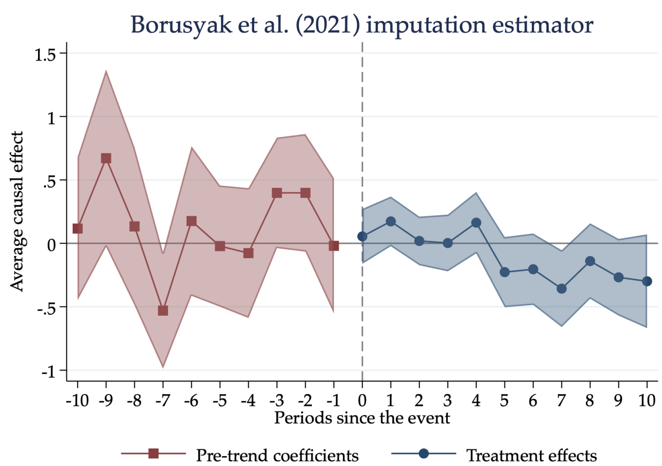
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.10: Event analysis: Effect of all solar policies on (log) capacity at 40th to 60th percentile of capacity



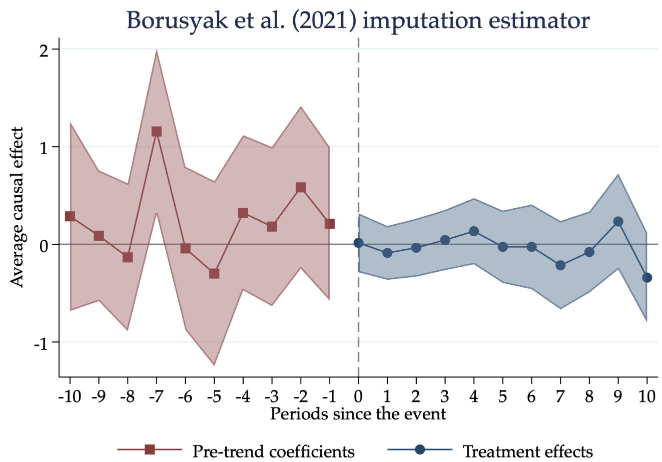
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.11: Event analysis: Effect of all solar policies on (log) capacity at 60th to 80th percentile of capacity



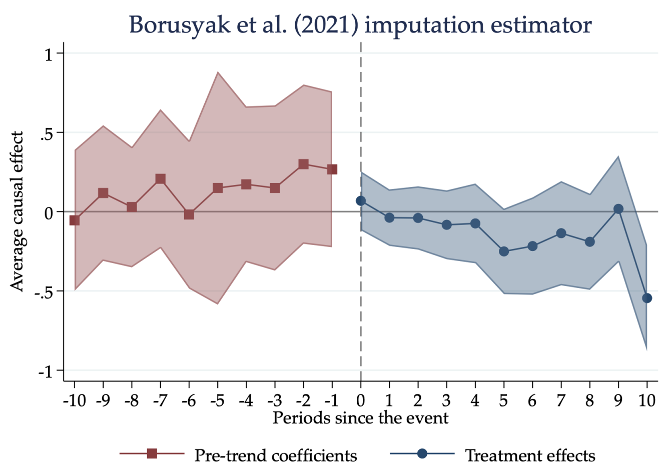
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.12: Event analysis: Effect of all solar policies on (log) capacity above the 80$^{\text{th}}$ percentile of capacity



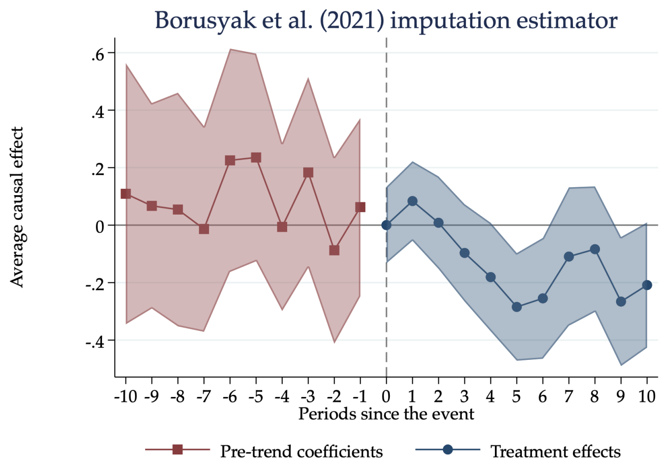
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.13: Event analysis: Effect of all solar policies on (log) capacity



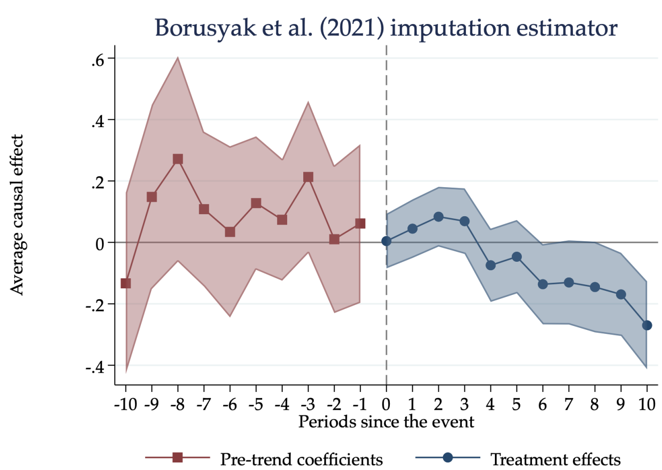
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.14: Event analysis: Effect of all solar policies on (log) capacity below the 20^{th} percentile of capacity



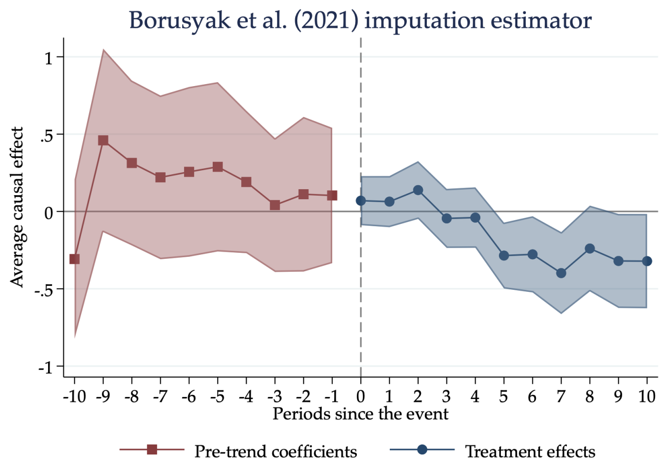
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.15: Event analysis: Effect of all solar policies on (log) installations at 20^{th} to 40^{th} percentile of capacity



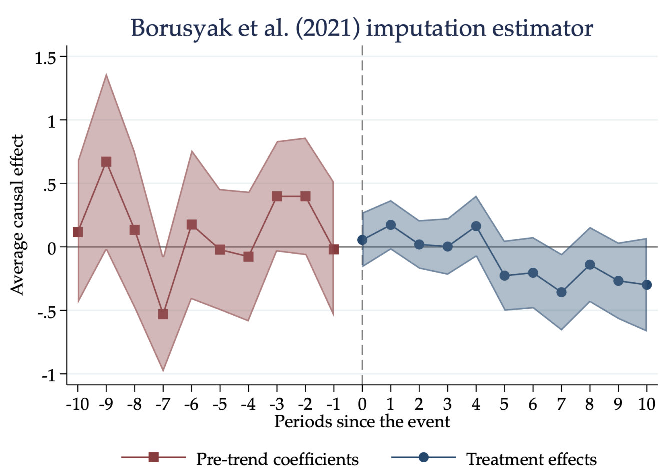
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.16: Event analysis: Effect of all solar policies on (log) capacity at 40th to 60th percentile of capacity



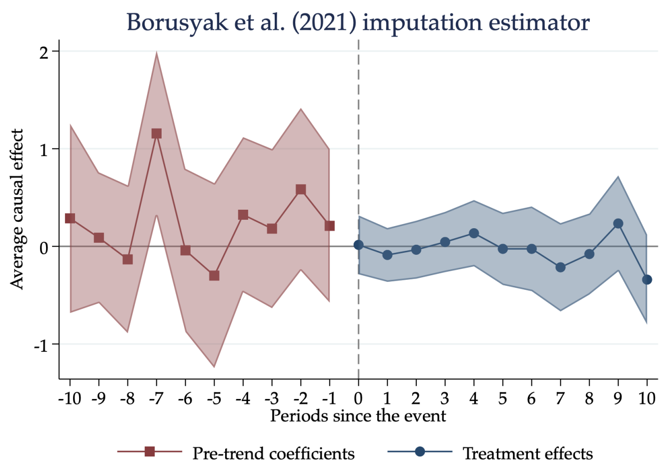
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.17: Event analysis: Effect of all solar policies on (log) capacity at 60th to 80th percentile of capacity



Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

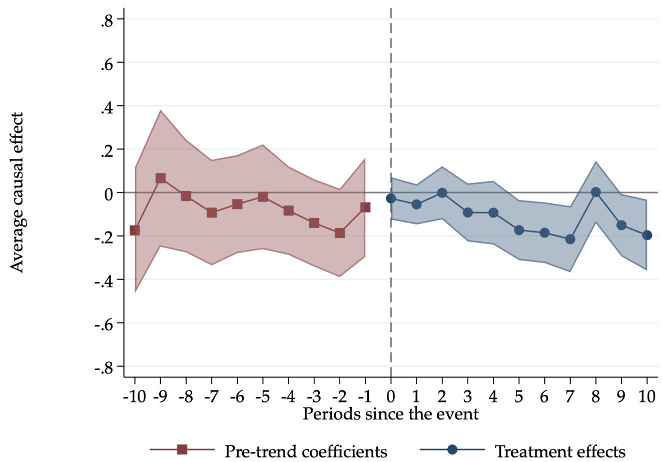
Figure C.18: Event analysis: Effect of all solar policies on (log) capacity above the 80^{th} percentile of capacity



Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

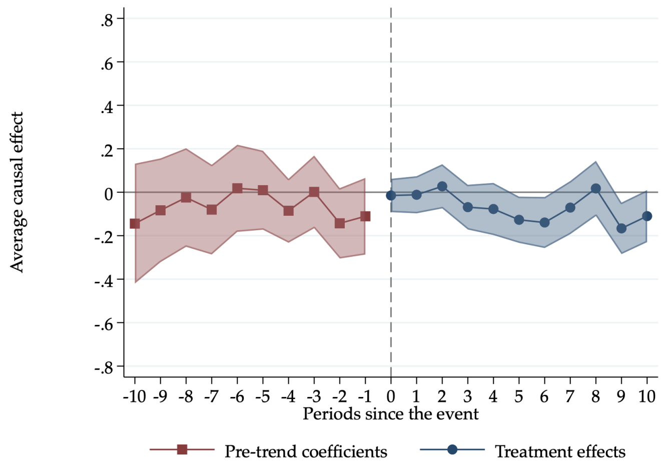
C.2 Unmatched Sample: Permits and Regulations

Figure C.19: Event analysis: Effect of all solar policies on (log) installations



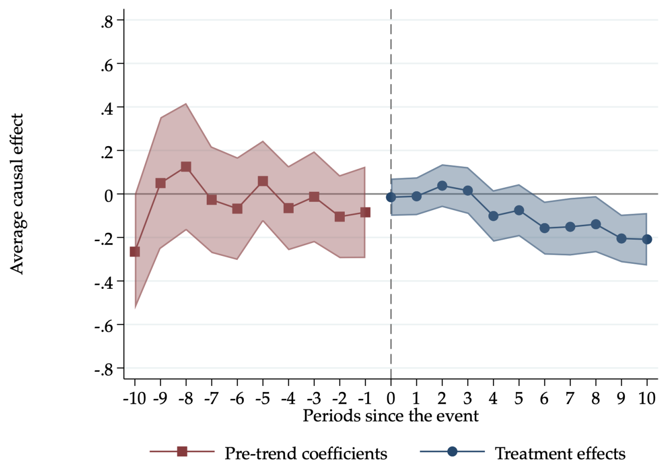
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.20: Event analysis: Effect of all solar policies on (log) installations below the 20^{th} percentile of capacity



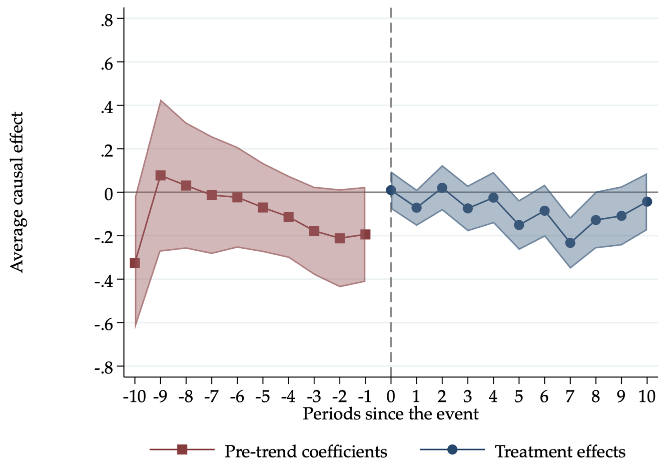
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.21: Event analysis: Effect of all solar policies on (log) installations at 20^{th} to 40^{th} percentile of capacity



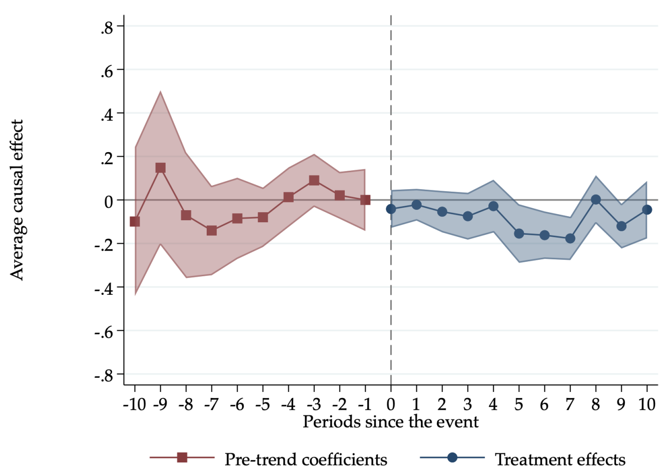
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.22: Event analysis: Effect of all solar policies on (log) installations at 40th to 60th percentile of capacity



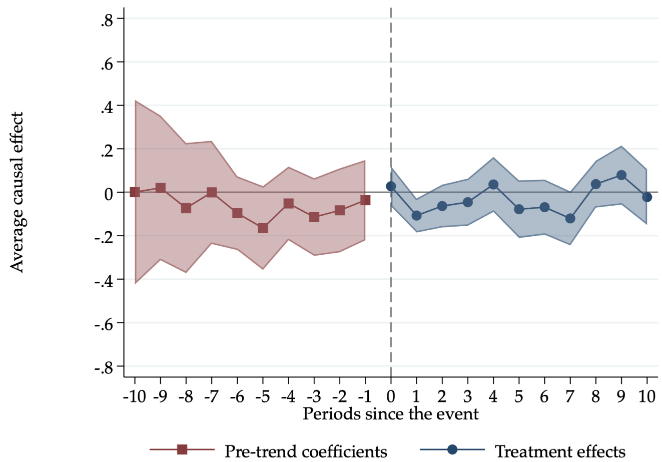
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.23: Event analysis: Effect of all solar policies on (log) installations at 60th to 80th percentile of capacity



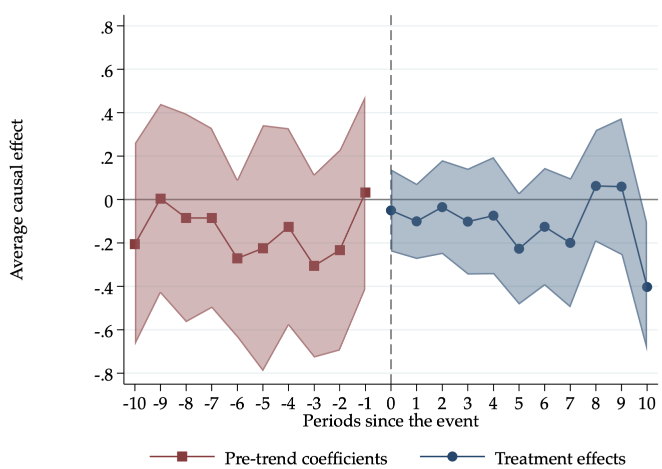
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.24: Event analysis: Effect of all solar policies on (log) installations above the 80th percentile of capacity



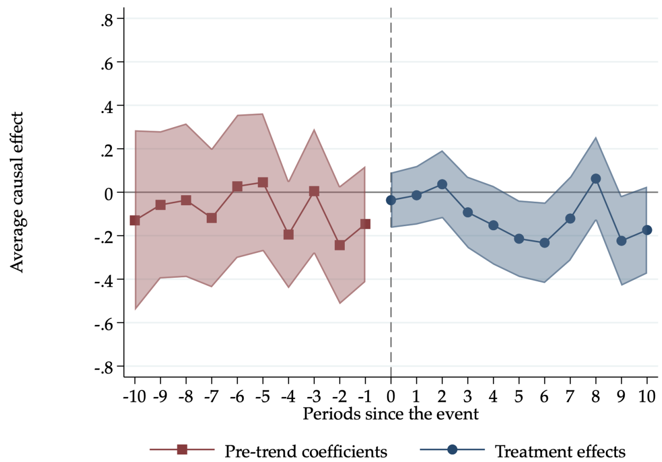
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.25: Event analysis: Effect of all solar policies on (log) capacity



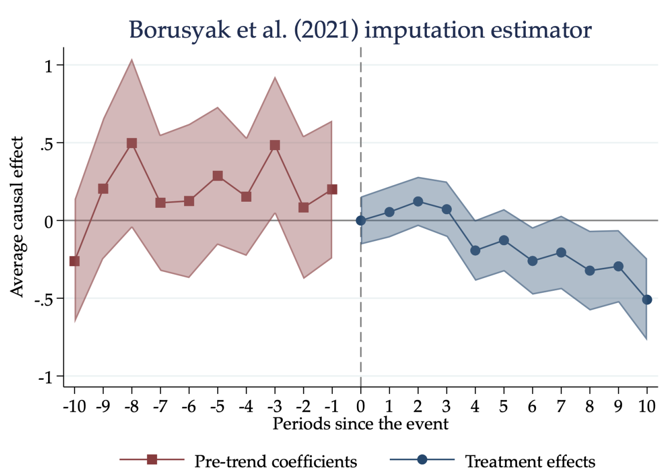
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.26: Event analysis: Effect of all solar policies on (log) capacity below the 20th percentile of capacity



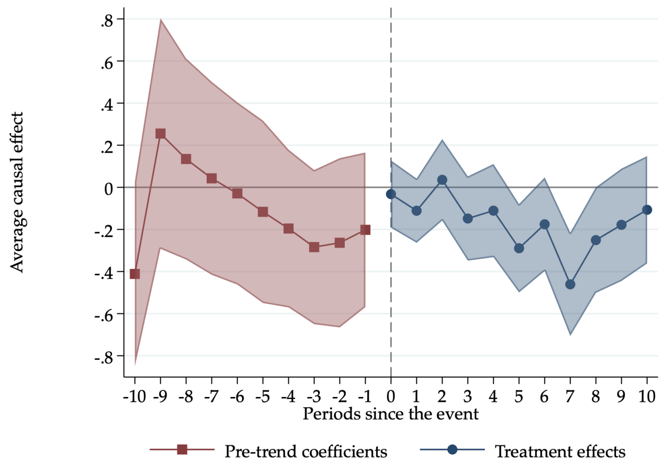
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.27: Event analysis: Effect of all solar policies on (log) capacity at 20th to 40th percentile of capacity



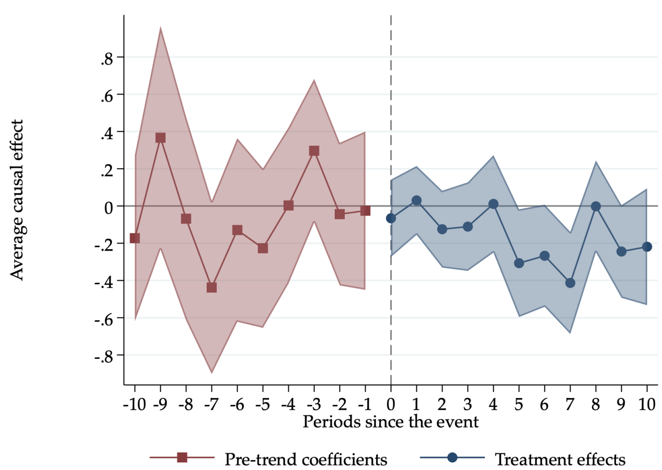
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.28: Event analysis: Effect of all solar policies on (log) capacity at 40^{th} to 60^{th} percentile of capacity



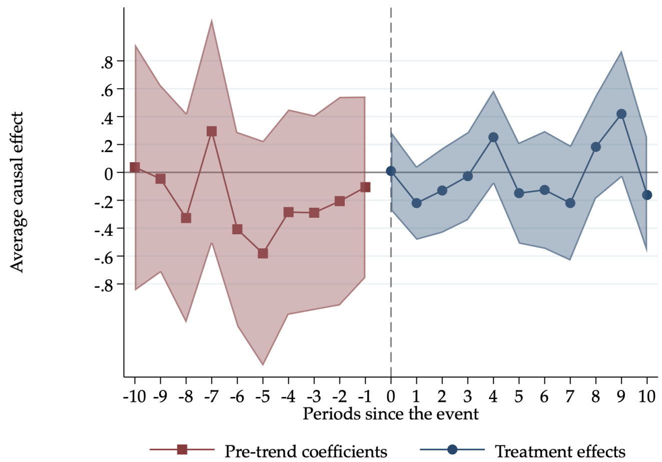
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.29: Event analysis: Effect of all solar policies on (log) capacity at 60^{th} to 80^{th} percentile of capacity



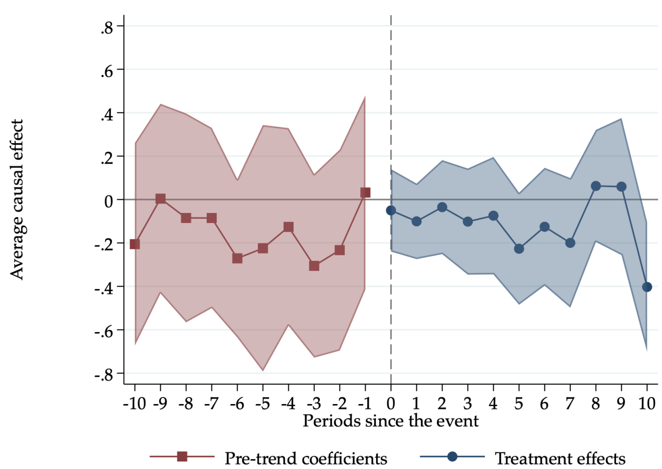
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.30: Event analysis: Effect of all solar policies on (log) capacity above the 80th percentile of capacity



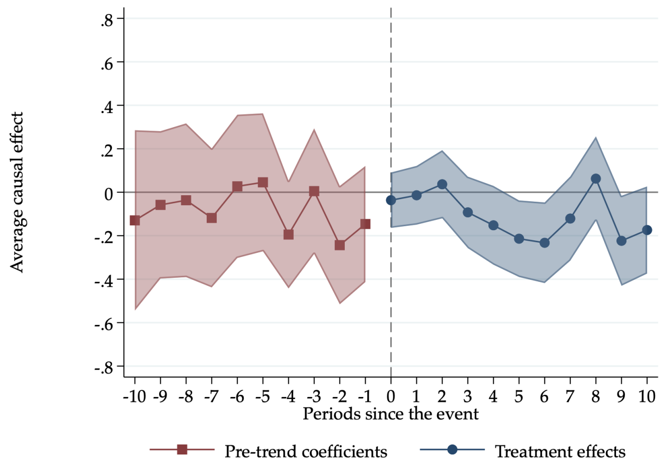
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.31: Event analysis: Effect of all solar policies on (log) capacity



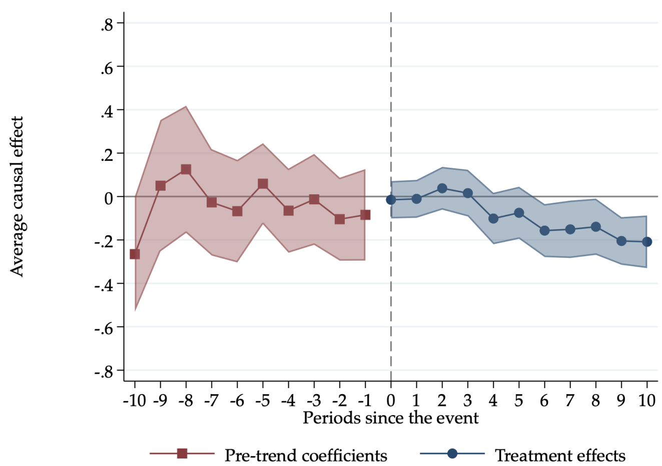
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.32: Event analysis: Effect of all solar policies on (log) capacity below the 20th percentile of capacity



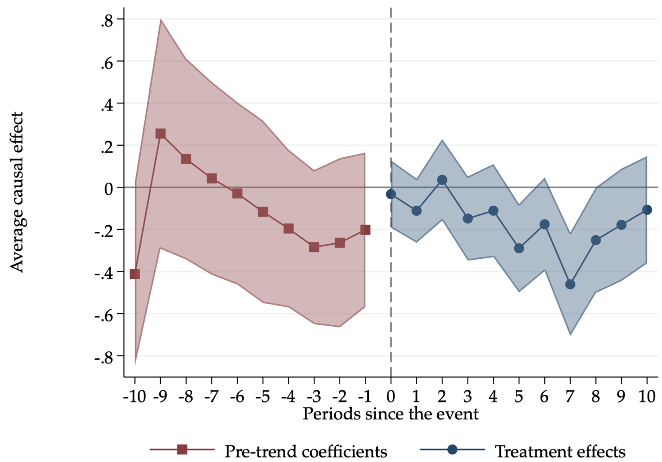
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.33: Event analysis: Effect of all solar policies on (log) installations at 20th to 40th percentile of capacity



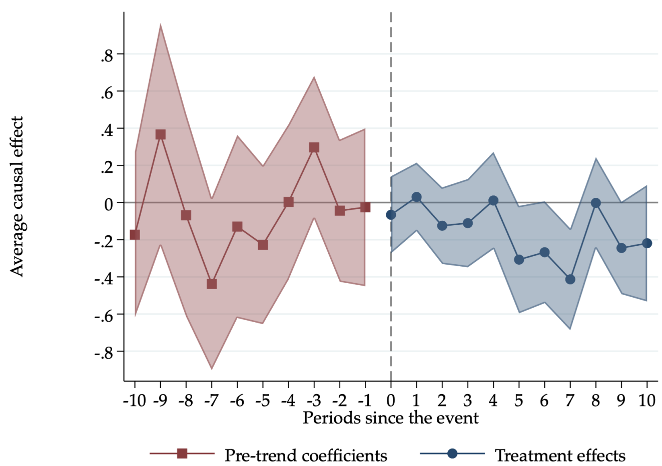
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.34: Event analysis: Effect of all solar policies on (log) capacity at 40^{th} to 60^{th} percentile of capacity



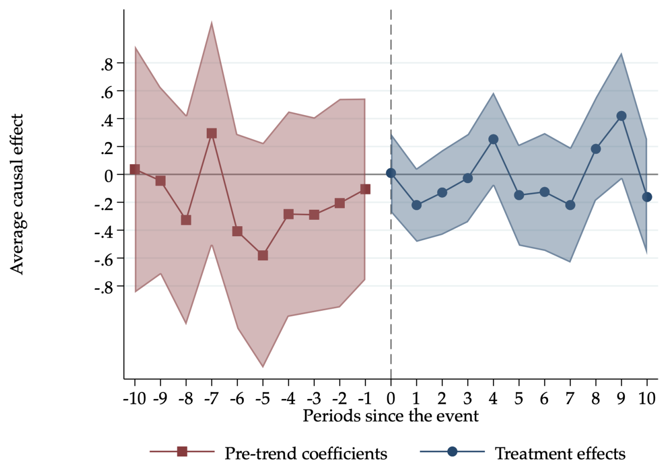
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.35: Event analysis: Effect of all solar policies on (log) capacity at 60^{th} to 80^{th} percentile of capacity



Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

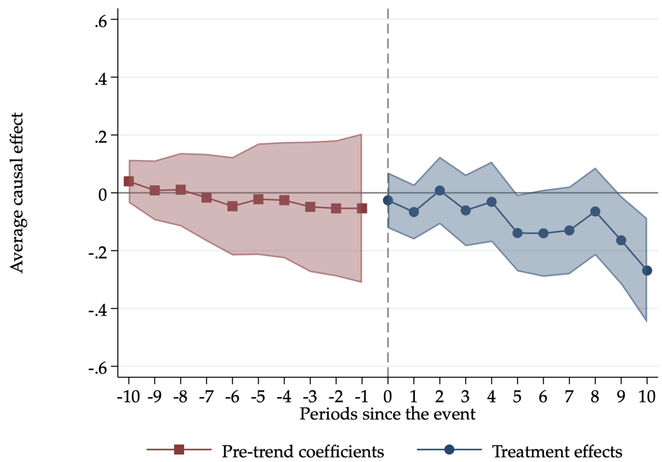
Figure C.36: Event analysis: Effect of all solar policies on (log) capacity above the 80th percentile of capacity



Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

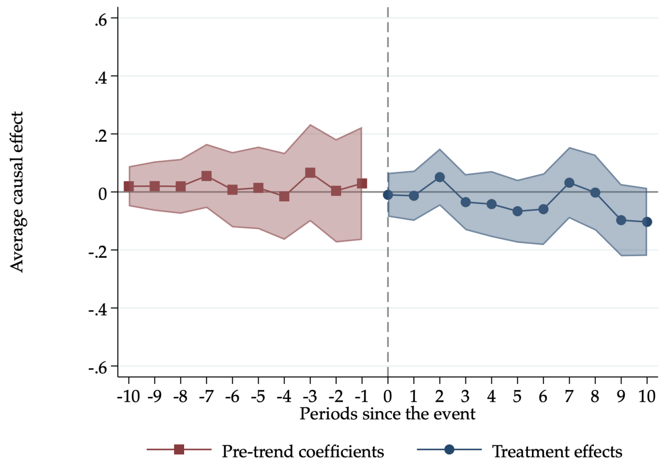
C.3 Matched Sample: All Solar Policies

Figure C.37: Matched sample event analysis: Effect of all solar policies on (log) installations



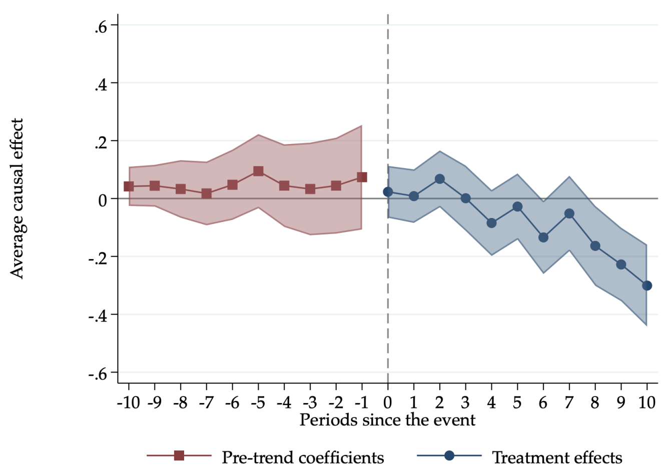
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.38: Matched sample event analysis: Effect of all solar policies on (log) installations below the 20th percentile of capacity



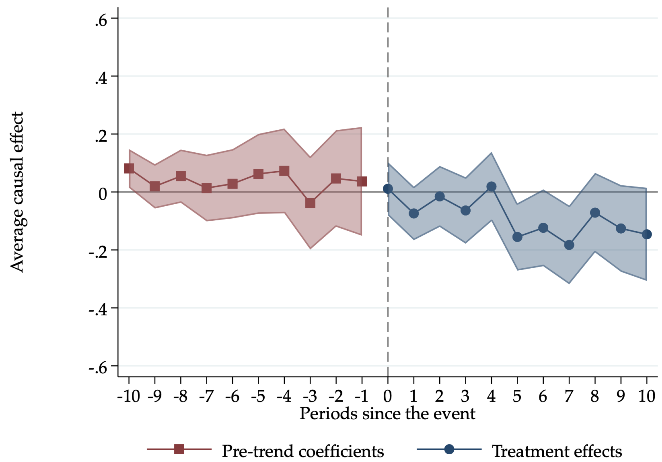
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.39: Matched sample event analysis: Effect of all solar policies on (log) installations at 20th to 40th percentile of capacity



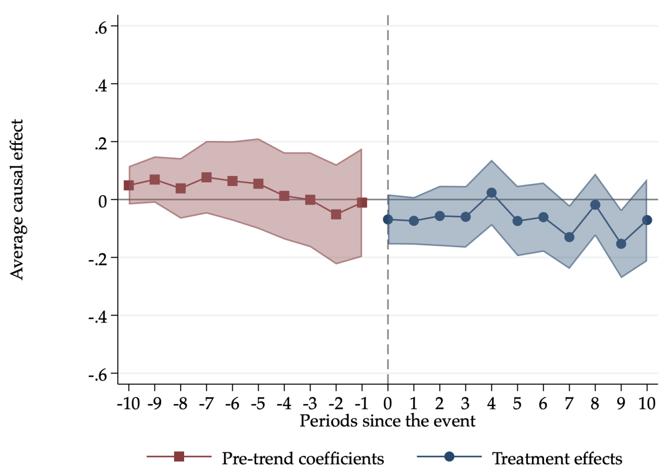
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.40: Matched sample event analysis: Effect of all solar policies on (log) installations at 40th to 60th percentile of capacity



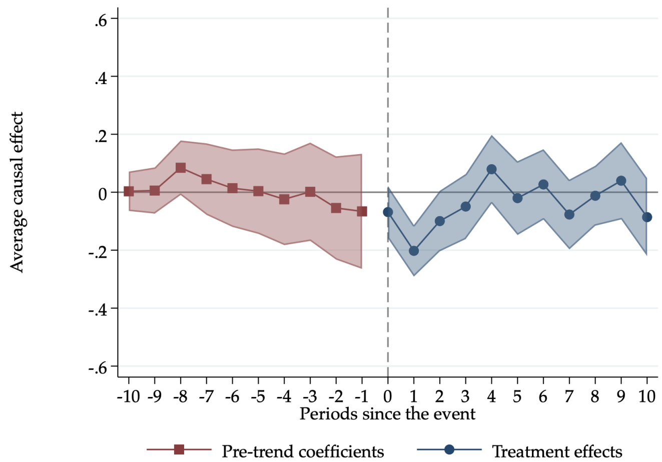
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.41: Matched sample event analysis: Effect of all solar policies on (log) installations at 60th to 80th percentile of capacity



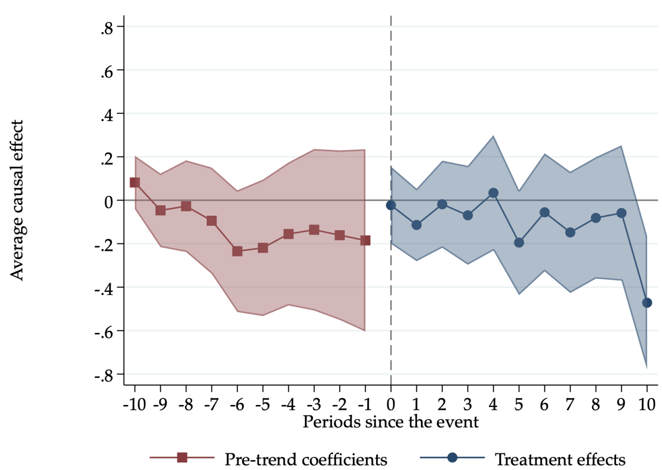
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.42: Matched sample event analysis: Effect of all solar policies on (log) installations above the 80$^{\text{th}}$ percentile of capacity



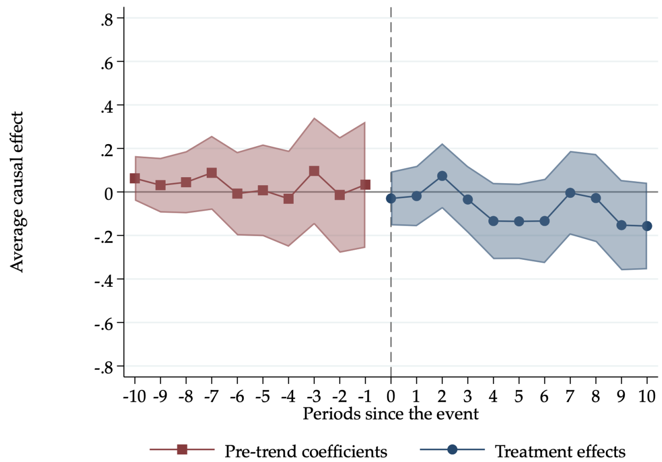
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.43: Matched sample event analysis: Effect of all solar policies on (log) capacity



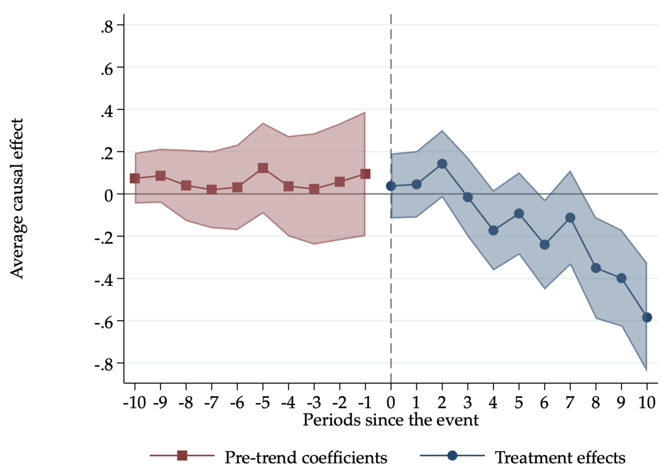
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.44: Matched sample event analysis: Effect of all solar policies on (log) capacity below the 20th percentile of capacity



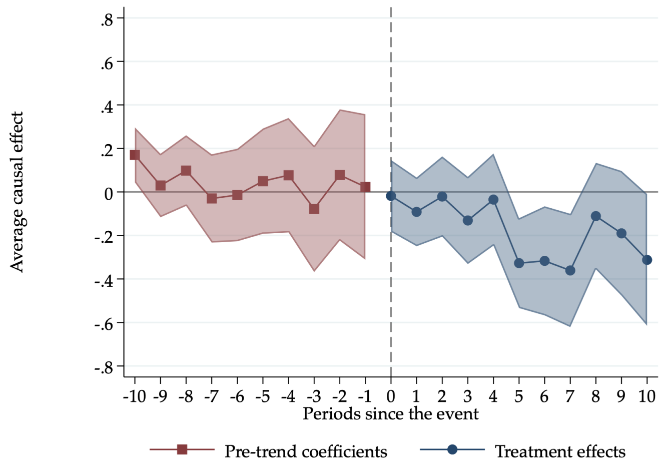
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.45: Matched sample event analysis: Effect of all solar policies on (log) capacity at 20th to 40th percentile of capacity



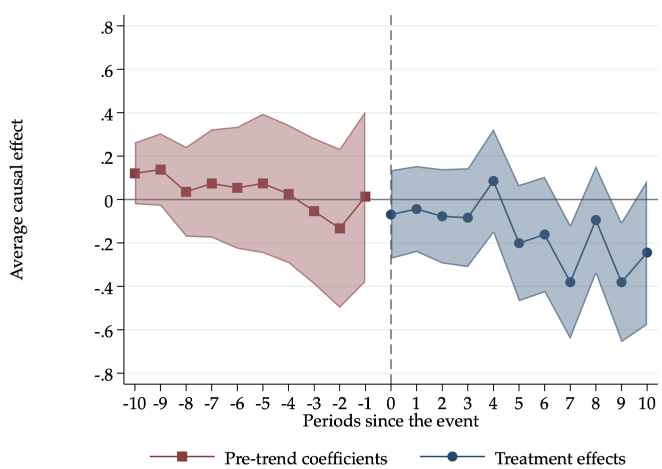
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.46: Matched sample event analysis: Effect of all solar policies on (log) capacity at 40^{th} to 60^{th} percentile of capacity



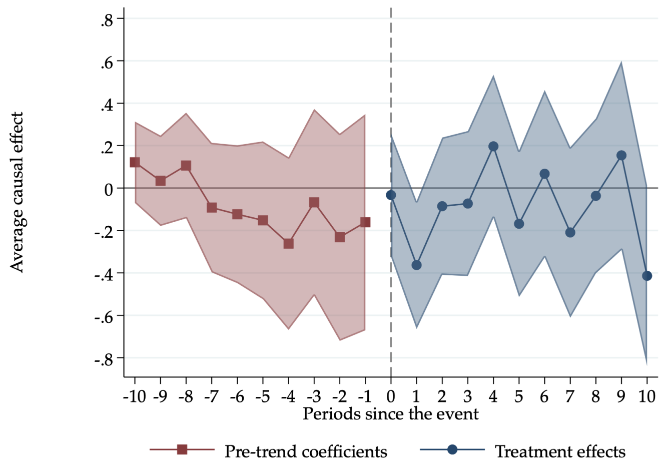
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.47: Matched sample event analysis: Effect of all solar policies on (log) capacity at 60^{th} to 80^{th} percentile of capacity



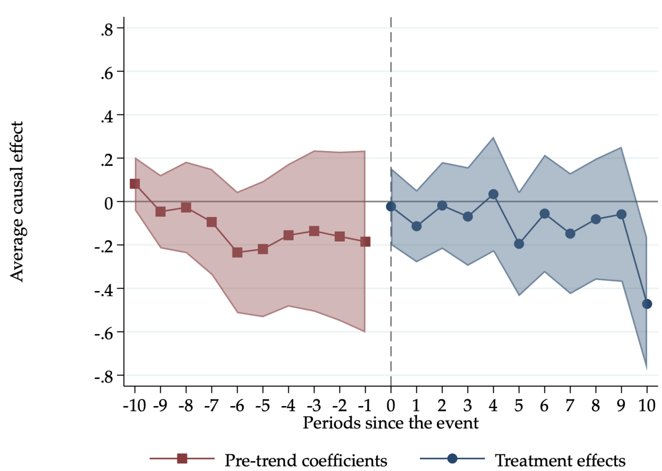
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.48: Matched sample event analysis: Effect of all solar policies on (log) capacity above the 80th percentile of capacity



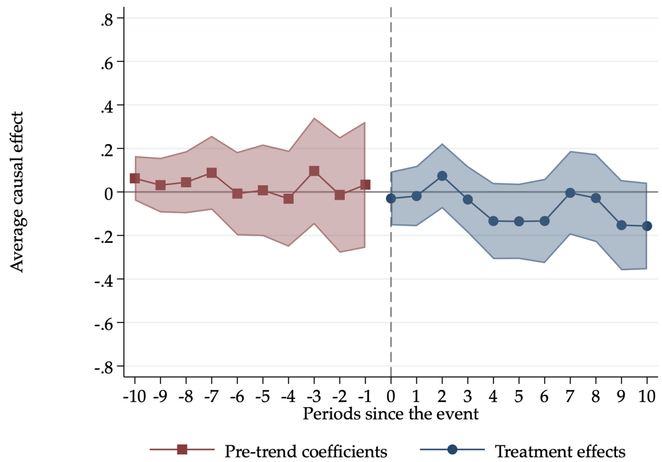
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.49: Matched sample event analysis: Effect of all solar policies on (log) capacity



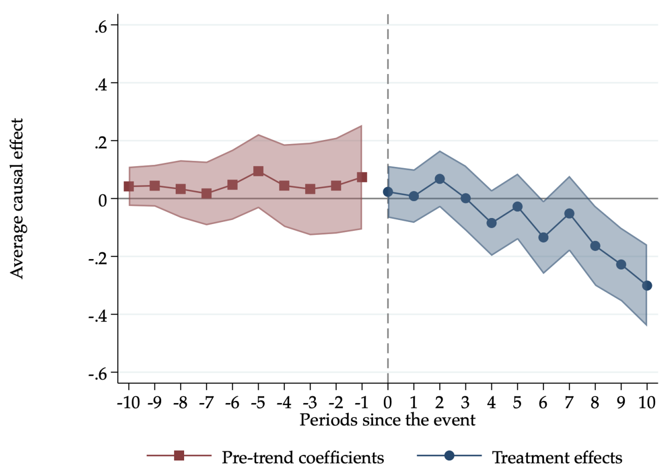
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.50: Matched sample event analysis: Effect of all solar policies on (log) capacity below the 20th percentile of capacity



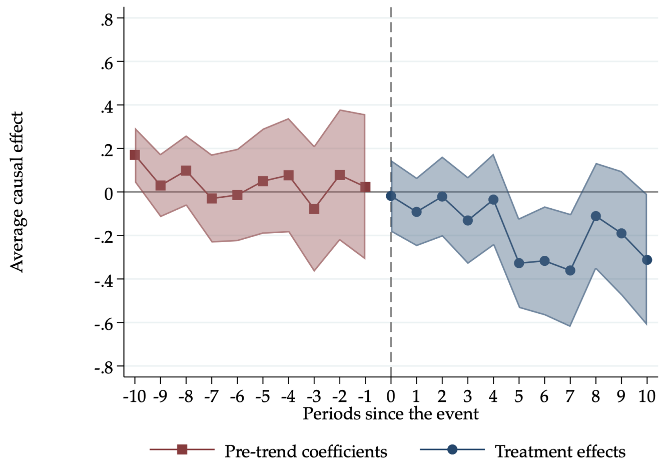
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.51: Matched sample event analysis: Effect of all solar policies on (log) installations at 20th to 40th percentile of capacity



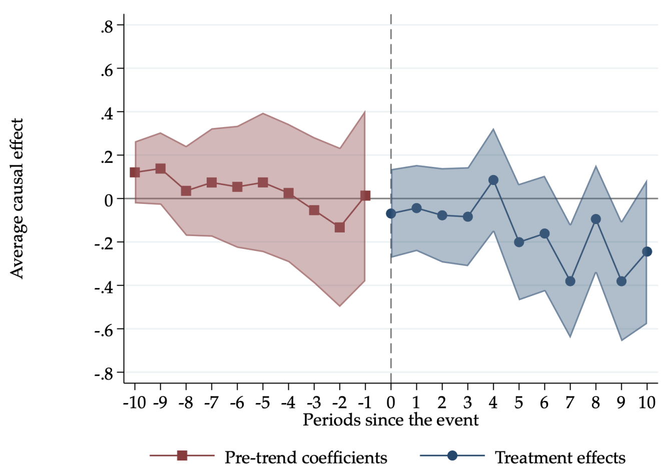
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.52: MATCHED SAMPLE EVENT ANALYSIS: EFFECT OF ALL SOLAR POLICIES ON (LOG) CAPACITY AT 40TH TO 60TH PERCENTILE OF CAPACITY



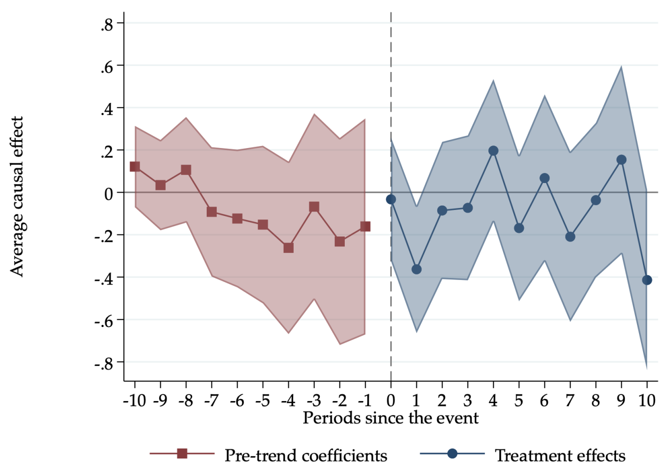
Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.53: MATCHED SAMPLE EVENT ANALYSIS: EFFECT OF ALL SOLAR POLICIES ON (LOG) CAPACITY AT 60TH TO 80TH PERCENTILE OF CAPACITY



Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

Figure C.54: Matched sample event analysis: Effect of all solar policies on (log) capacity above the 80th percentile of capacity



Borusyak et al. (2021) imputation estimator. 95 percent confidence intervals indicated by shaded area.

D Additional robustness tests

In this Appendix Section, we present additional variants of our main specifications, in order to assess the robustness of our findings.

D.1 Continuous treatment

Our main specification studies the treatment effect of a municipal solar policy as a canonical binary policy effect. In reality, some municipalities implement solar policies that apply only to a subset of the total land area of the municipality. Therefore, our analyses include an additional set of estimations where we account for area-specific policies using a continuous variable.

The treatment variable of interest takes value zero if no solar policy is in place, one if the municipality implemented a policy that applies to its entire land area, and a value corresponding to the share of the total urban area that is treated if the policy is spatially targeted.

This continuous treatment variable relies on land use categorization data,[13] in which urban land with many buildings that may have rooftop solar installed is categorized as either “continuous urban fabric” (Durchgängig städtische Prägung) or “discontinuous urban fabric” (Nicht durchgängig städtische Prägung). Our treatment intensity measure is thus the fraction of the total urban fabric which is covered by the policy. The values corresponding to the share of the total land area that is treated are constructed using the detailed policy documents, maps, and shapefiles provided by the municipalities.

The two-way fixed effect estimation using the continuous treatment variable identifies an average causal response (ACR), which captures a weighted average of causal responses to a unit change in treatment (Angrist and Imbens, 1995). Intuitively, this can be thought of as a treatment dose. Callaway and Sant’Anna (2021) discuss the implications of identifying the ACR in a generalized difference-in-differences framework. They show that a stronger parallel trend assumption needs to hold in a scenario with multiple time periods and staggered

[13] Specifically, on the CORINE Land Cover (CLC) database, 2018 edition, maintained by Germany’s geodesy agency (Bundesamt für Kartographie und Geodäsie).

adoption of continuous treatments. This stronger assumption restricts paths of treated potential outcomes by treatment dose group: All dose groups treated at a particular time need to follow the same path of potential outcomes at every dose. We believe that our argument in support of the parallel trend assumption in the binary treatment case may extend to the continuous case. Moreover, it is plausible that, for example, a ban of solar installations that applies to 60 percent of an urban area implies a solar capacity trajectory not substantially different from a ban that applies to 30 percent of an area. In other words, we expect a reduction in capacity twice as large in the case of a 60 percent area ban compared to the ban on solar in 30 percent of the urban area. The coefficients in Table D.1 are significantly larger than the main results in Table 5, typically almost twice in magnitude. This makes sense, considering that the binary treatment is imperfectly capturing treatment intensity if only part of a municipality is treated. Therefore, the continuous treatment estimates suggest that the main results are to be considered as conservative lower-bound estimates.

Table D.1: Effect of any policy on solar adoption, treatment intensity

	(1) Log Capacity	(2) Log Installs
All installations	-0.213*	-0.152*
	(0.125)	(0.0833)
1^{st} quintile	-0.152*	-0.0954*
	(0.0845)	(0.0549)
2^{nd} quintile	-0.237**	-0.143**
	(0.110)	(0.0679)
3^{rd} quintile	-0.249**	-0.134*
	(0.123)	(0.0694)
4^{th} quintile	-0.211*	-0.0956*
	(0.121)	(0.0561)
5^{th} quintile	-0.325*	-0.118*
	(0.176)	(0.0638)
Time-varying controls	Yes	Yes
N	33169	33169
Adj. R^2	0.617	0.643
Adj. within R^2	0.00691	0.0104

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.2: Effect of permits & regulations on solar adoption, treatment intensity

	(1) Log Capacity	(2) Log Installs
All installations	-0.361**	-0.254**
	(0.169)	(0.104)
1st quintile	-0.246***	-0.149**
	(0.0928)	(0.0621)
2nd quintile	-0.366***	-0.195**
	(0.138)	(0.0824)
3rd quintile	-0.400***	-0.204**
	(0.146)	(0.0805)
4th quintile	-0.344**	-0.150**
	(0.157)	(0.0679)
5th quintile	-0.309	-0.108
	(0.206)	(0.0721)
Time-varying controls	Yes	Yes
N	9523	9523
Adj. R^2	0.627	0.651
Adj. within R^2	0.0118	0.0124

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

D.2 Additional Robustness Tests

Table D.3: Effect of any policy on solar adoption (inverse hyperbolic sine transformed outcome)

	(1) Log Capacity	(2) Log Installs
All installations	-0.0573	-0.0954*
	(0.0802)	(0.0539)
1st quintile	-0.104*	-0.0647
	(0.0578)	(0.0418)
2nd quintile	-0.136*	-0.0938**
	(0.0697)	(0.0466)
3rd quintile	-0.210***	-0.125***
	(0.0752)	(0.0466)
4th quintile	-0.113	-0.0645
	(0.0790)	(0.0443)
5th quintile	-0.0721	-0.0657
	(0.106)	(0.0464)
Time-varying controls	Yes	Yes
N	33169	33169
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.669	0.661
Adj. within R^2	0.00804	0.0107

Standard errors clustered at the municipality-level.

Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.4: Effect of permits & regulations on solar adoption (inverse hyperbolic sine transformed outcome)

	(1) Log Capacity	(2) Log Installs
All installations	-0.190**	-0.194***
	(0.0896)	(0.0587)
1st quintile	-0.186***	-0.123***
	(0.0618)	(0.0447)
2nd quintile	-0.259***	-0.160***
	(0.0752)	(0.0493)
3rd quintile	-0.316***	-0.186***
	(0.0820)	(0.0483)
4th quintile	-0.270***	-0.144***
	(0.0868)	(0.0459)
5th quintile	-0.149	-0.0909*
	(0.112)	(0.0469)
Time-varying controls	Yes	Yes
N	43721	43721
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.667	0.661
Adj. within R^2	0.00832	0.00982

Standard errors clustered at the municipality-level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.5: Effect of any policy on solar adoption, treatment intensity (inverse hyperbolic sine transformed outcome)

	(1) Log Capacity	(2) Log Installs
All installations	-0.0790	-0.122
	(0.105)	(0.0792)
1st quintile	-0.138*	-0.0912
	(0.0811)	(0.0572)
2nd quintile	-0.195*	-0.138**
	(0.103)	(0.0672)
3rd quintile	-0.263**	-0.160**
	(0.114)	(0.0678)
4th quintile	-0.151	-0.0846
	(0.124)	(0.0650)
5th quintile	-0.136	-0.0937
	(0.147)	(0.0653)
Time-varying controls	Yes	Yes
N	33169	33169
Adj. R^2	0.669	0.661
Adj. within R^2	0.00832	0.0113

Standard errors clustered at the municipality-level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.6: Effect of permits & regulations on solar adoption, treatment intensity (inverse hyperbolic sine transformed outcome)

	(1) Log Capacity	(2) Log Installs
All installations	-0.197	-0.221**
	(0.133)	(0.0974)
1st quintile	-0.231**	-0.149**
	(0.0947)	(0.0683)
2nd quintile	-0.307**	-0.194**
	(0.126)	(0.0827)
3rd quintile	-0.381***	-0.228***
	(0.146)	(0.0846)
4th quintile	-0.309**	-0.168**
	(0.155)	(0.0778)
5th quintile	-0.195	-0.115
	(0.170)	(0.0732)
Time-varying controls	Yes	Yes
N	31378	31378
Adj. R^2	0.683	0.677
Adj. within R^2	0.00996	0.0132

Standard errors clustered at the municipality-level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.7: EFFECT OF ANY POLICY ON SOLAR ADOPTION (2000-2019)

	(1) Log Capacity	(2) Log Installs
All installations	-0.0940	-0.0668
	(0.107)	(0.0494)
1st quintile	-0.106*	-0.0656*
	(0.0616)	(0.0390)
2nd quintile	-0.154**	-0.103**
	(0.0766)	(0.0439)
3rd quintile	-0.0833	-0.0368
	(0.0850)	(0.0488)
4th quintile	-0.121	-0.0602
	(0.0933)	(0.0433)
5th quintile	-0.294*	-0.112**
	(0.158)	(0.0528)
Time-varying controls	Yes	Yes
N	13140	13140
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.565	0.637
Adj. within R^2	0.00494	0.0116

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.8: Effect of any policy on solar adoption, Exact match on historical status of municipality

	(1) Log Capacity	(2) Log Installs
All installations	-0.153	-0.108*
	(0.0970)	(0.0591)
1st quintile	-0.106*	-0.0673*
	(0.0601)	(0.0399)
2nd quintile	-0.154**	-0.0853*
	(0.0768)	(0.0483)
3rd quintile	-0.178**	-0.0866*
	(0.0860)	(0.0514)
4th quintile	-0.151*	-0.0716*
	(0.0840)	(0.0410)
5th quintile	-0.194	-0.0739
	(0.127)	(0.0468)
Time-varying controls	Yes	Yes
N	34369	34369
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.620	0.645
Adj. within R^2	0.00609	0.00885

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.9: Effect of any policy on solar adoption (exact matching within state)

	(1) Log Capacity	(2) Log Installs
All installations	-0.148	-0.104*
	(0.0991)	(0.0607)
1st quintile	-0.0952	-0.0591
	(0.0623)	(0.0420)
2nd quintile	-0.174**	-0.0972*
	(0.0784)	(0.0499)
3rd quintile	-0.181**	-0.0912*
	(0.0872)	(0.0523)
4th quintile	-0.131	-0.0568
	(0.0864)	(0.0424)
5th quintile	-0.183	-0.0650
	(0.130)	(0.0485)
Time-varying controls	Yes	Yes
N	30265	30265
Year FE	Yes	Yes
Municipality FE	Yes	Yes
Adj. R^2	0.631	0.656
Adj. within R^2	0.00565	0.00800

Standard errors clustered at the municipality-level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.10: Effect of any policy on solar adoption, removing Bavaria and Baden-Württemberg

	(1) Log Capacity	(2) Log Installs
All Installations	-0.255	-0.165
	(0.173)	(0.107)
1st quintile	-0.143	-0.0816
	(0.102)	(0.0669)
2nd quintile	-0.276*	-0.132
	(0.142)	(0.0876)
3rd quintile	-0.211	-0.0857
	(0.160)	(0.0890)
4th quintile	-0.166	-0.0622
	(0.151)	(0.0676)
5th quintile	-0.213	-0.0800
	(0.225)	(0.0780)
Time-varying controls	Yes	Yes
N	6804	6804
Adj. R^2	0.570	0.600
Adj. within R^2	0.00391	0.00704

Standard errors clustered at the municipality-level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Figure D.1: Effect of permits & regulations on solar adoption for 1st quintile installations, over 78 permutations removing 2 states at the time

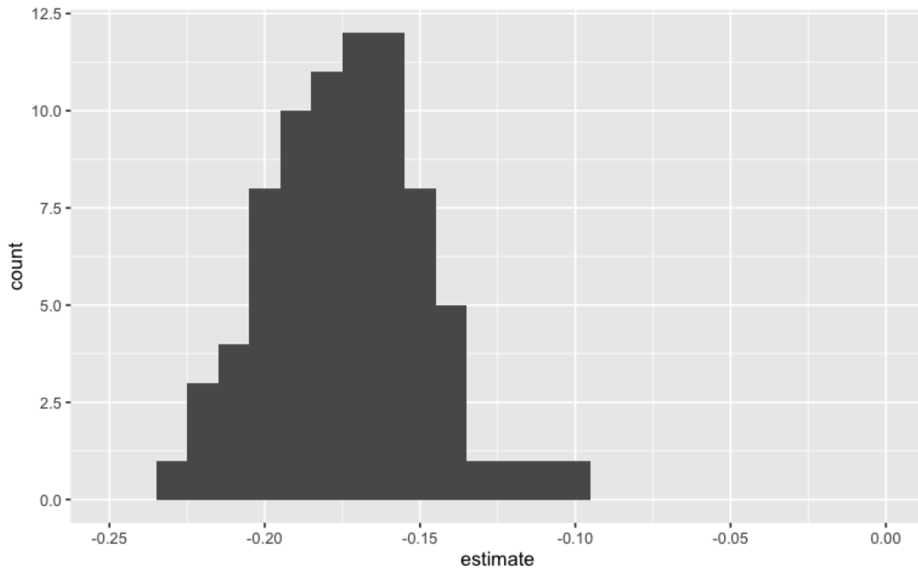


Table D.11: EFFECT OF ANY SOLAR POLICY ON SOLAR ADOPTION (1:1 MATCH)

	(1) Log capacity	(2) Log installs
All installations	-0.158	-0.102
	(0.105)	(0.0646)
1st quintile	-0.119*	-0.0648
	(0.0657)	(0.0442)
2nd quintile	-0.158*	-0.0735
	(0.0850)	(0.0539)
3rd quintile	-0.174*	-0.0732
	(0.0930)	(0.0565)
4th quintile	-0.105	-0.0492
	(0.0917)	(0.0446)
5th quintile	-0.116	-0.0447
	(0.138)	(0.0510)
Time-varying controls	Yes	Yes
N	11493	11493
Adj. R^2	0.618	0.639
Municipality FE	Yes	Yes
Year FE	Yes	Yes

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.

Table D.12: Effect of permits & regulations on solar adoption (1:1 match)

	(1) Log capacity	(2) Log installs
All installations	-0.235*	-0.143*
	(0.124)	(0.0739)
1st quintile	-0.135*	-0.0716
	(0.0763)	(0.0513)
2nd quintile	-0.185*	-0.0785
	(0.0950)	(0.0597)
3rd quintile	-0.235**	-0.0943
	(0.103)	(0.0609)
4th quintile	-0.153	-0.0633
	(0.105)	(0.0500)
5th quintile	-0.112	-0.0282
	(0.153)	(0.0548)
Time-varying controls	Yes	Yes
N	9019	9019
Adj. R^2	0.614	0.634
Municipality FE	Yes	Yes
Year FE	Yes	Yes

Standard errors clustered at the municipality level.
Significance levels: * $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$.