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«Ground-Mounted Solar and The Impact of Land-Use Planning: Evidence from France»

by

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Ground-mounted solar and the impact of land-use planning: evidence from France *

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Abstract

This paper provides novel evidence on how land-use regulation impacts the deployment of solar photovoltaic installations in France. Solar energy projects must meet eligibility criteria to participate in renewable energy auctions, based on the land used by the installation. Eligibility criteria, in turn, are transposed in land-use planning at the municipality level. Using an event study, I investigate how this interaction impacts the amount of land allocated to solar. My findings suggest that the fragmentation and heterogeneity of land-use planning may distort the spatial deployment of solar. Municipalities with more detailed land-use planning increase the amount of land allocated to solar by an average of 1,000 m^2 per km^2 of land eligible for new developments. Conversely, more recent land-use planning and frameworks integrated at the inter-municipality level reduce the amount of land by -1,500 m^2 per km^2, due to stricter restrictions on new land developments.

Keywords: land-use regulation, land-use planning, policy decentralization, renewable energy auctions, solar photovoltaic, staggered difference-in-differences.

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1 Introduction

The European Union (EU) has committed for a massive and rapid deployment of renewable energy (RE) supply in electricity generation (European Commission, 2023).

Access to suitable land is crucial to achieve this objective. Utility-scale solar and wind power facilities use at least ten times more land than conventional power plants, such as gas or nuclear, for the same installed capacity (Nøland et al., 2022) and cannot be developed anywhere. They need sufficient levels of solar irradiation and wind speed to be profitable. They can also generate negative externalities when installed close to human settlements (Gibbons, 2015; Dröes and Koster, 2021; Maddison et al., 2023), or biodiversity losses from induced conversion of natural land (Hernandez et al., 2014).

Command-and-control policy instruments are implemented across countries to address these tradeoffs, encompassed in land-use regulation. How, and to what extent, can public interventions improve the efficiency of the spatial deployment of renewable energy remains an important policy question to address. Recent articles have studied the effects of different policy instruments, notably in Germany and in the UK (Meier et al., 2023; Lehmann and Tafarte, 2024; Lehmann et al., 2023; Delafield et al., 2024), and obtained important results. While effectively directing RE installations, land-use regulation can hardly solve the arbitrages mentioned above. For example, policies aiming at reducing conversion of natural land, such as exclusion areas, could either increase disamenity costs or investments costs required to achieve a given energy target. Alternatively, policies aiming at reducing local disamenities, such as set-back distances between wind turbines and nearby dwellings, likely increase the conversion of natural land.

Another potential channel of inefficiency stems from the fact that policy instruments can be partially decentralized for implementation. In many countries, municipalities have authority on land-use regulation (OCDE, 2017). Hence, rules enacted at the national level to frame the spatial deployment of RE must be coordinated with lower jurisdiction levels. However, the multiplicity of local jurisdictions can give rise to inefficiencies, either due to divergent local incentives to promote RE supply, or from failures in implementing and enforcing the regulation (Winikoff, 2022; Meier and Lehmann, 2022).

The present paper explores the impacts of land-use regulation on the deployment of utility-scale solar PV facilities that are installed directly on the ground (referred as ground-mounted in this paper). France provides a unique and internationally relevant[1] setting to study how decentralized spatial planning policies and coordination between administrative layers affects the deployment of RE supply. Notably, the country has a very fragmented territory with more than 34,000 municipalities that set their own land-use regulation.

The setting examined in the paper is as follows. The French national energy regulator (CRE) sets eligibility criteria in solar energy auctions to allow projects that are located on certain types of land plots in the bidding process. In turn, eligibility criteria are defined based on regulations in place in municipalities, namely land-use planning frameworks. However, not all municipalities have the same regulatory framework to define their land-use planning. As of today, 40% of French municipalities use a land-use planning framework that allows them to differentiate, at most, between land that can be developed or land that must be kept in its natural state. The other 60% use a detailed land-use planning framework with more than ten categories to discriminate between different types of land-uses. Land-use planning also change with the scale at which they are implemented, either integrating grouped municipalities (i.e. inter-municipality) or a single one. They are also approved at different years.

I apply an event study approach to investigate the impact of a change in land-use planning on the local development of ground-mounted solar. I construct a data-set that keeps track of past transitions in land-use planning frameworks across municipalities this past decade, matched to the history of commissioning of solar installations. I use *staggered difference-in-differences (DiD)* specifications to assess the impact of a type of land-use planning on the amount of land allocated to ground-mounted solar several years after its approval. I compare municipalities that updated their land-use planning (treatment group) to their counterparts that are in the process of updating their land-use planning to a similar framework (control

[1] Countries that have given responsibility for land-use planning to municipalities, that have enhanced legislation on land conservation, and national public auctions to deploy renewable energy follow a similar logic.

group).

I find that land-use planning frameworks impact the commissioning of solar installations along three key dimensions: (1) frameworks with more detailed land-use categories increase the amount of land allocated to ground-mounted solar by an average of 1,000 m^2 per km^2 of land eligible for new developments, (2) more up-to-date frameworks reduce the amount of land by -1,500 m^2 per km^2, (3) integrated land-use planning at the inter-municipality level reduce the amount of land by -1,500 m^2 per km^2. Estimates become significant 5 years after the approval of a new land-use planning.

These findings are robust to different threats to the identification of a causal impact. First, both land-use planning and the permitting of ground-mounted solar involve different levels of governance, which reduces the risk of reversed causality. Land-use planning is elaborated by the municipality, whereas project developers ask for a building permit to central state devolved authorities (*préfets*). The decision of state devolved authorities is independent of the municipality and taken on the basis of an administrative process involving the appraisal of several expertise authorities. Second, the ongoing transition of land-use planning frameworks observed across municipalities this past decade is largely driven by national legislation.[2] Land-use planning frameworks arguably serve as valid instruments for estimating the causal impact of regulation on solar development. The type of framework in place at the local level affects the amount of land eligible for solar, depending on its alignment with top-level regulations, while being independent of the stringency of land-use regulation chosen by the locality. Third, sensitivity analyses support the robustness of the DiD for causal identification. To assess parallel trends, I conduct the regression after propensity score matching based on land-use patterns and, alternatively, after inclusion of socio-economic characteristics as covariates. I also test the stability of the treatment – spatial interferences between treated units and its neighbors – by introducing spatial buffers between treatment and control groups.

[2]Two milestone refroms are the "SRU" law (2000), which has created a new regulatory framework to enshrine land-use planning at the local level framework; and the "ALUR" law (2014), which initiated the gradual integration of land-use planning at the inter-municipality level.

This paper shows that the diversity of regulatory frameworks that are used to establish land-use planning change the amount of land eligible for solar facilities. First, more detailed land-use planning frameworks enable better targeting and access of public subsidies to suitable land -– solar projects participating in public auctions. This is explained by a regulatory effect. The national energy regulator favors solar projects on the land plots allowed for construction. Thus, eligibility criteria are better aligned with more detailed land-use planning, which can discriminate between different categories of land developments. I identify this effect as a *static* policy implementation failure. National energy auctions are not well aligned with the diversity of local frameworks, which steers solar installations in certain areas not due to their inherent social value, but simply because the regulatory framework makes permitting easier.

Second, more up-to-date land-use planning – those designed in recent years and integrated at the inter-municipality level – present more constraints to the siting of ground-mounted solar facilities. I explore mechanisms that could explain this result and find three different channels. First, land conservation objectives were gradually formalized in national legislation and passed through in municipalities' land-use planning.[3] The staggered implementation of national legislation at the local level hence give opportunities to project developers to dump stricter regulations by targeting localities that are lagging in the application of new regulation. I identify this phenomenon as a *dynamic* policy implementation failure.

A second mechanism is that integrated land-use planning at the inter-municipality level come with an additional planning tool, namely the local Climate Air Energy Plan (PCAET), which can set precise targets for renewable energy development and other environmental policy objectives. However, local authorities could use this tool to reflect local preferences by putting more focus on the external costs of local RE development, to the detriment of their global climate mitigation benefits. As such, PCAETs could restrict the local development of solar facilities in place of other environmental priorities such as land conservation. I explore this mechanism by exploiting a population threshold at which PCAETs are mandatory for

[3] Land conservation objectives has been gradually formalized in the French legislation from Grenelle I and II laws (2010) to the Climate and Resilience law (2021), which has enshrined binding objectives to reduce the rate of new land takes in municipalities.

inter-municipalities. The effect of integration conditional of being above the population threshold is higher in magnitude than for municipalities below.

A last potential mechanism could stem from consequences of inter-municipal cooperation (Tricaud, 2025). Induced changes in tax bases among local jurisdictions of the inter-municipality could modify the incentives of local authorities to allocate land to solar. After integration, the local benefits of commissioning a solar facility, i.e. specific tax revenues, have to be shared among the different jurisdictions of the inter-municipality, while disamenity costs are still falling on the municipal government through local elections.

These mechanisms are real-world examples of inefficiencies that may arise upon the decentralization of environmental policies. For long analyzed in light of the environmental and fiscal federalism literature (Oates, 1999), the question of the optimal allocation of governance for the deployment of renewable energy has become timely and important. On the one hand, RE deployment require local intervention, notably to tackle information asymmetries and match local voters' preferences. On the other hand, given that RE produces nationwide benefits, local jurisdictions have low incentives to allocate land to RE development, putting more weight on the local costs of their allocation. I add to this (theoretical) literature by uncovering specific channels through which co-regulation between national and local governments can fail to achieve an efficient spatial deployment of RE (Meier and Lehmann, 2022)

This paper also contributes to the literature studying the spatial determinants of the deployment of renewable energy. Literature shows that peer-effects and NIMBY effects can play a key role in steering RE installations (Jarvis, 2021; Carlisle et al., 2016; Bollinger and Gillingham, 2011), as well as the development of electricity grids (Gonzales et al., 2023; de Lagarde, 2018), and localized market-based policy instruments (Hitaj and Löschel, 2019). Land-use regulation, however, has received smaller attention. Research has focused to a great extent on the deployment of wind power and the impact of policy instruments such as designated areas, protected areas or set-back distances (Lehmann et al., 2023; Lehmann and Tafarte, 2024; Delafield et al., 2024; Reutter et al., 2024) using spatial modeling approaches. Empirical research on the *ex-post* effects of land-use regulation is scant. To my knowledge, the only studies examining the effects of land-use regulation are Meier et al. (2023), which investigates the impacts of priority areas in spatial planning on wind power development in Germany, and Stede and May (2020), which analyzes the effect of setback distance regulations on wind power permitting in Bavaria (Germany). In contrast to this literature, I focus on local land-use planning and the deployment of ground-mounted solar installations.

2 Institutional background

France plans a fourfold increase of solar photovoltaic (PV) capacity between 2020 and 2030 (*Programmation Pluriannuelle de l'Energie*, 2019), involving the deployment of 2 GW of additional capacity per year in utility-scale solar installations installed on the ground (i.e. ground-mounted installations). Despite the lack of precise data we can deduct from cumulative installed capacity figures that around 90% of ground-mounted solar in France were developed under public support schemes (France Territoire Solaire, 2023). Since 2011, France relies on specific auctions to develop ground-mounted solar PV. They are organized by the French Energy Regulation Commission (CRE). The past four iterations of public auctions allocated a volume of 7.5 GW to ground-mounted solar installations. The 5th iteration (called *"CRE 5"*) is aiming at an additional 9 GW capacity by 2026 (France Territoire Solaire, 2023).

2.1 How to develop ground-mounted solar facilities?

Project developers have to follow key steps to secure suitable land for the installation of ground-mounted solar. First, they must find a land plot that is eligible on a number of technical aspects. The land plot must be located in a close perimeter to electricity grids' substations.[4] The land plot must be of sufficient size to host a ground-mounted solar installation. Auctions specific to ground-mounted solar specify a minimum size of 0.5 MW and

[4]in France, ground-mounted solar facilities connect either to the medium voltage level of the distribution grid (HTA) or to the higher voltage level (HTB). Most units connecting to either the HTA or HTB level incur grid connection costs. These costs consist of building/reinforcing power lines connecting the unit to the upstream substation. In France, a rule of thumb states that the grid connection length must be less than 1 kilometer per MW of installed capacity to ensure reasonable connection costs.

a maximum size of 17 MW, which correspond to areas ranging between 1 and 30 hectares. The land plot must have a good solar orientation and entail low civil works. Although all regions in metropolitan France have sufficient solar irradiation levels for developing solar, it remains an important enabler of project development, since higher levels significantly reduce production costs. Finally, solar PV developers must agree on a long-term leasing contract with the land owner.

Second, project developers must obtain a building permit before construction. For renewable energy projects, permit-granting is specifically done by a central state representative (*préfet*). Permit-granting is done after systematic appraisal of project application files by expertise state devolved and regional authorities. The project application file is realized beforehand by project developers and contains an environmental impact assessment, as well as risks and feasibility assessments when required. The scrutiny of project appraisal varies conditional on the type of land where the project is located. For example, if the project is in an area identified as natural land, the project will go under specific appraisal of the *Commission for the Preservation of Natural, Agricultural and Forest areas (CDPENAF)*, which assesses clear cutting conditions, endangered fauna and flora species, or the loss in wetland associated with its development. According to the context, the CDPENAF can impose drastic technical changes to the project or disapprove permitting. Finally, the project has to go through a consultative process with local population, conducted by a state inspector, before final approval of the *préfet*. Figure A.12 in appendix describes main steps of the permit-grating procedure.

After obtaining a building permit, solar PV developers have to get an authorization to connect to the electricity grid and to secure a power purchasing contract, most often through public auctions. The overall time frame between the building permit application and the commissioning of the project is thus very variable and on average takes between 3 and 5 years.

2.2 Land-use planning frameworks

Municipalities are the lower of the three main administrative levels in France (*Régions, Départements, Communes*) and divide the french territory in more than 34,000 units. Each municipality is governed by a municipal council, directly elected from the local population. They have authority over a series of local public services, raise local taxes and are in charge of land-use planning. Municipalities are also part of an inter-municipality, a jurisdiction regrouping neighboring municipalities. Local public services can be transferred to the inter-municipality to leverage economies of scale, such as waste management or public transportation.[5] Since 2014, land-use planning is also being transferred to the inter-municipality level.[6]

Land-use planning comprises all rules to restrict or allow new land developments. Land-use planning frameworks provide zonal maps to allow or restrict new land takes and identify the type of activities that can be developed within a territory. One particularity of France is that there is a variety of land-use planning frameworks that can be used by municipalities. First, they vary by the by the number of land-use categories they have to designate different types of land use. Municipalities can elaborate a *Carte Communale (CC)*. *CC* is a framework that only discriminate between land authorized to be developed and land that must be kept in natural state. Municipalities can also elaborate a *Plan Local d'Urbanisme (PLU)*. *PLU* provide more detailed categories of land-uses and specific orientations. The PLU has four main categories of land-use developments, that can be further identified in subcategories. For example, within land authorized for new developments, they can differentiate between several categories to identify the type of activity (e.g. housing, commercial, mixed developments). Municipalities can also choose not to have zoning and follow the *Reglement National d'Urbanisme (RNU)*, which sets general rules for land development. Typically, the

[5] Integrating inter-municipalities was not compulsory until 2010. All municipalities are now part of an inter-municipality containing at least 5,000 inhabitants. Inter-municipalities are governed by a board of municipal council members and vote on which public services and policies will be transferred to the upper-tier jurisdiction.

[6] After last municipal elections in 2020, land-use planning is by law under the jurisdiction of inter-municipalities. However, municipalities can keep their jurisdiction if at least 25% of municipalities representing 20% of the population are against the transfer of competencies.

RNU states that new buildings constructions can only be developed nearby urbanized areas. Second, land-use planning frameworks vary by the administrative scale at which they are elaborated. For example, when under inter-municipalities, the *PLU* framework becomes a *PLU-i*. Third, land-use planning frameworks display important variation in their time of approval. There is no requirement to update land planning in a frequent manner. As of 2023, more than 20% of municipalities have a land-use planning approved before 2014.

Land-use planning regulation has gradually evolved since last decades driven by subsequent reforms. New legislation mainly aimed at upgrading the former land-use planning framework, called *POS*, to the *PLU*; and gradually transferring land-use planning under the jurisdiction of inter-municipalities.[7]. Moreover, land conservation policies – objectives to reduce the rate of new land developments – have been progressively integrated into legislation, beginning with the "Grenelle II" Law in 2011 and culminating in the 2021 "Climate and Resilience" Law, which enshrines the goal of achieving net zero land development by 2030 for all municipalities.

These regulatory changes have been implemented heterogeneously across the territory. For instance between 2012 and 2023 we observe:

- About 2,000 municipalities under a *CC* and 3,000 municipalities under the *RNU* that have upgraded to a *PLU* or *PLU-i*,
- About 6,000 municipalities either in *CC* or *RNU* frameworks that are still in the process of upgrading to a *PLU* or *PLU-i*,
- About 4,000 municipalities under the older framework, named *POS*, that have yet updated to a *PLU* or *PLU-i*,
- About 3,000 municipalities under a *PLU* that integrated to a *PLU-i* framework, while 4,000 municipalities that are still in the process of approving one.

[7]Notable milestone legislation is as follows: the"SRU" law (2000) introduced the *PLU* to replace *POS*. The law of December 16, 2010 mandated the integration of municipalities into inter-municipalities. The "ALUR" law (2014) transferred jurisdiction over land-use planning to the inter-municipality level. The "ALUR" law has also set an expiry date for land-use planning frameworks under *POS* to switch to *PLU*.

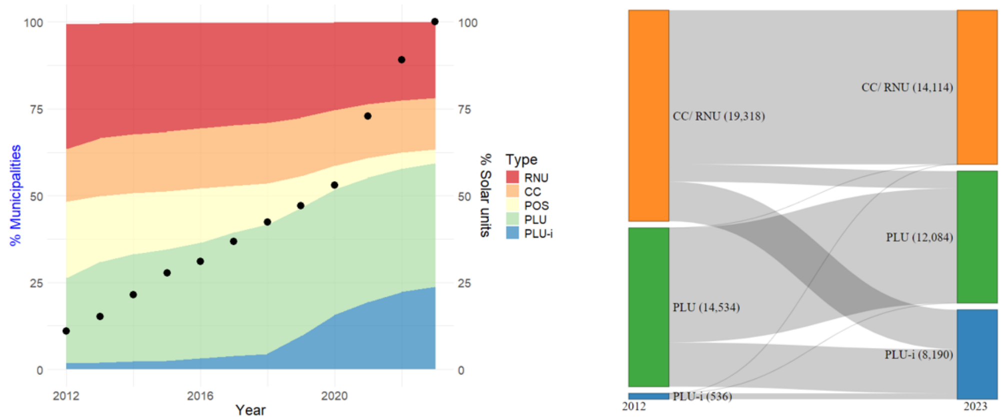

Figure 1: Shifts of land-use planning frameworks between 2012 and 2023 across French municipalities and cumulative deployment of ground-mounted solar units.

Figure 1 displays the shifts of land-use planning frameworks that occurred during this period. We can see on the left panel that the transition in land-use planning across municipalities coincides with the deployment of ground-mounted solar installations.

Process for elaborating land-use planning. The creation or upgrade of land-use planning is a task initiated and approved by the (inter-)municipal council. Its elaboration results from a multi-levelled governance process as follows. (1) The municipal council starts by elaborating a local development plan, which has to comply with upper-tiers' strategic orientations.[8] During its design, a panel of public entities give their feedback to the document such as neighboring municipalities, upper-tier administrations, and the *préfet*. (2) The regional environmental authority conducts an environmental impact assessment of the provisional land-use planning. (3) Land-use planning undergoes a public consultation process with local inhabitants. (4) The council approves the finalized land-use planning and is made available to the public. Figure A.13 in appendix A depicts the main steps in the elaboration process of land-use planning.

[8]Regional authorities (*Régions*) issue strategic orientations in documents called *SRADDET* which are renewed every 5 years. Sub-regional authorities (*Départements*) integrate regional objectives in strategic documents called *SCOTs*. Inter-municipalities can issue strategic planning in relation to specific themes such as local Climate Air Energy Plans (*PCAET*) or local Housing Plans (*PLH*).

The complexity of the elaboration process makes the time for approval highly uncertain. On average there are 3-5 years between the prescription of a new framework and its approval. *PLU-i* makes the process even longer, resulting from a bargaining process between member municipalities, and having to integrate more elements such as *Local Housing Plans (PLH)* and *local Climate Air Energy Plans (PCAET)* in the land-use planning.

2.3 Land-use regulation for ground-mounted solar

As detailed above, the permitting process of ground-mounted solar varies with the type of land on which it is located. The central administration follows an approach called "avoid-reduce-compensate", which prioritizes in first, already developed land with no potential other usages such as stranded or polluted sites; in second, the land deemed eligible for new developments.; in last, the land identified as a natural area or hosting agricultural activities. The french energy regulator (CRE) has formalized this approach by setting eligibility criteria for participating in national auctions for ground-mounted solar.[9] Applicants are eligible if and only if the land on which the project is located meets one of the following options:

- Case 1: project site located in a land plot that allows for new land developments, identified as labels U or AU in a *Plan Local d'Urbanisme (PLU)*.

- Case 2: project site located in a land plot that allows for new developments in a *Carte Communale (CC)*, identified by the label ZC. Otherwise, project site located in a land plot that does not allow for new land developments but that specifically authorize activities linked to renewables, identified by labels N-enr, N-pv or N-e in *PLU*. In this case, additional authorizations regarding clear cutting conditions, fauna and flora or wetlands are required.

- Case 3: project site located in an area deemed polluted or damaged that is listed in national inventories (e.g. old quarry and mines, stranded industrial sites, landfills, soil pollution)

[9] Certificate of Eligibility for the Land Settlement (CETI) introduced in 2016. First auctions for ground-mounted solar (between 2011 and 2015) only graded candidates offers according to the location of the project: good grades for already artificialized and damaged lands, bad grades for natural and agricultural spaces.

In addition, a part of the total grade (10-20%) for bidders is given conditional on the quality of the site, where best scores are awarded to damaged or polluted sites (Case 3) and the worst to natural and agricultural areas (Case 2).

Such articulation between top-level criteria and land-use planning frameworks may significantly change the local amount of land eligible for solar. For example, land plots authorized for new developments in *PLU* are directly eligible to the development of ground-mounted solar, whereas land identified for new developments in *CC* requires additional appraisal and get a lower grade in solar energy auctions. Moreover, land plots under the *Reglement National d'urbanisme (RNU)* are in principle not eligible to national energy auctions, although this framework is in place in 27% of municipalities as of 2023.

2.4 Conceptual framework

This paper aims to estimate the impact of land-use regulations on the amount of land allocated to solar facilities. Land-use regulation for solar pertains to the joint regulatory setting described above: where eligibility criteria defined by the energy regulator are being transposed in land-use planning at the municipality level. Ideally, one would estimate the elasticity of land allocated to solar relative to the quantity of land deemed eligible by regulation. However, two challenges arise. The amount of land eligible at the municipality level is not completely observed,[10] and the impact of regulation on solar could be biased by various confounders. For example local opposition to renewables can interfere with both the content of land-use planning and solar deployment, or projects developers could solicit municipalities upstream to modify their zoning rules and accommodate the siting of their facility.

To overcome these challenges, I hinge on the heterogeneity of land use planning frameworks to instrument changes in the amount of land eligible for solar. First, adopting a new type of land-use planning framework – i.e. changing from a *CC* to a *PLU* framework – likely affects the amount of land deemed eligible to solar. Each framework use a differ-

[10] Existing datasets from the *Institut national de l'information géographique et forestière* only provide cross-sectional zoning information for about 60% of municipalities

ent set of land-use categories to designate land development, hence changing the quantity of areas eligible for solar installations due to (mis)alignments with national regulation, as detailed above. Alternatively, a new type of land-use planning framework can also change broader strategic orientations for spatial planning. In this case, while not impacting land-use categories in zonal maps, it changes the amount of land allocated to each of them.

Second, a new type of land-use planning framework should be independent of confounders that affect both solar development and the quantity of eligible land in the locality. This is true for several reasons: (1) changing the regulatory framework is not meant to hinder or facilitate the development of solar *per-se*. Municipal authorities can decide on the level of stringency of land-use regulation conditional on having a type of land-use planning framework. (2) Adopting a new land-use planning framework is arguably independent of reversed causality biases. As detailed above, the elaboration process involves the appraisal and authorization of a number of public expertise authorities that should, in principle, prevent the strategic manipulation of land-use planning by specific stakeholders. (3) Exogenous changes in national legislation have mainly driven important shifts in land-use planning observed this last decade among french municipalities. (4) Once a municipality is in the process of elaborating its new land-use planning framework. The time of approval is highly uncertain given the administrative procedure to appraise and give final approval without specific deadlines. Figure A.14 in Appendix A shows an histogram of the length of elaboration of land-use planning across municipalities. We see significant variation, 80% of municipalities spend between 2 to 7 years to complete their land-use planning. The length of elaboration seems to follows a normal distribution with a mean of 5 years and standard deviation of 2 years. I will exploit, in a quasi-experimental setting, variations in the timing of the approval of new land-use planning to uncover a causal impact of a change in regulation – *Average Treatment on the Treated (ATT)*. Arguably, there are no threats of selection biases based on the timing of approval of a new land-use planning.

Building on the institutional background, I identify three dimensions of land-use planning frameworks that might change the amount of land deemed available to ground-mounted solar installations. The intensities of each dimension are detailed in Table 1:

1. Level of detail of land-use planning. This is given by land-use categories that can be identified in the land-use planning framework. *PLU(-i)* frameworks provide the most details, *CC* frameworks and *RNU* framework provide the least details.

2. Administrative scale of land-use planning. PLU-i are elaborated at the inter-municipality level, while other frameworks are done at the municipal level

3. Time of approval of land-use planning. There is no clear deadline to update land-use planning in a frequent manner. Hence, we observe a significant variability regarding the time of approval of land-use planning over the last decade.

Table 1: Dimensions of land-use planning

	RNU	CC	POS	PLU	PLU-i
Detail	L	M	H	H	H
Scale	L	L	L	L	H
Time	M	M	L	M	M

Note: Letters are used to indicate the intensity of each dimension in each framework: L for low; M for medium; H for high.

I then draw three propositions on the directions of the impacts of a change of land-use planning frameworks (along each dimension) on the amount of land deemed eligible to ground-mounted solar installations.

First, I posit that more detailed land-use planning have more land deemed eligible to solar by regulation and thus unlocks more land for ground-mounted solar installations. This is driven by eligibility criteria defined by the CRE which are better aligned with *PLU* frameworks. This leads to the following proposition:

Proposition 1: Municipalities upgrading their land-use planning to a PLU framework increase the amount of land allocated to ground-mounted solar, all else equal.

Second, I posit that more recent land-use planning frameworks unlocks less land eligible to ground-mounted solar. Legislation on land conservation has been progressively formalized in recent years. Hence, municipalities that have land-use planning approved prior to the enactment of recent legislation have likely not yet integrated the latter objective in their spatial planning policy.

Proposition 2: Municipalities adopting a more recent PLU decrease the amount of suitable land for ground-mounted solar, all else equal.

Third, I posit that elaborating land-use planning at the inter-municipality level unlocks more land for ground-mounted solar. Following Tricaud (2025), I expect that the integration in inter-municipalities has an overall positive effect on land development. Besides, this effect should be higher for municipalities that have less weight in the bargaining process of the inter-municipality or for municipalities that were reluctant to integrate the latter. This leads to the following proposition:

Proposition 3: Municipalities adopting a PLU-i increase the amount of suitable land for ground-mounted solar, all else equal.

3 Empirical strategy

I implement an event study approach to estimate differences in the amount of land allocated to solar between municipalities that have updated to a new land-use planning framework and municipalities that have not yet updated to a similar framework. Hence, I recover an average impact on treated municipalities, Considering the long and uncertain administrative procedure for elaborating a land-use planning, the year of approval can be considered quasi-random and there is arguably no selection of municipalities into a specific timing. The identification of a causal impact holds as long as land allocated to solar follows parallel trends in controlled and treated municipalities without the change in land-use planning, and that there is no interferences between units upon the treatment. The validity of these assumptions is discussed in Section 3.2.

3.1 Econometric model

I focus on a period spanning from 2010, which marks the beginning of the ground-mounted solar PV deployment in France, to 2023. I use a balanced panel of municipalities located in metropolitan France, excluding overseas territories and Corsica.

I implement a *staggered differences-in-difference (DiD)* model à la Sun and Abraham (2021) to control for potential biases arising with variation in treatment timing. My treatment group is made of municipalities that have updated or upgraded their land-use planning between 2012 and 2023. I consider different treatment groups conditional on the mechanism that I investigate: (a) municipalities that upgraded a *RNU* or *CC* to a *PLU* or *PLU-i*; (b) municipalities that updated their *PLU(-i)* during the period; (c) municipalities that integrated their land-use planning at the inter-municipality level (*PLU-i*). My control groups are made of municipalities that are not yet treated. The regression model is given in Equation (1):

$$Y_{i,t} = \sum_{d=-10}^{10} \beta_d 1[t = t_0 + d] + \mu_i + \rho_{r,t} + \epsilon_{i,t} \tag{1}$$

where the year of approval of new land-use planning is denoted by t_0 and treatment dummies $1[t = t_0 + d]$ are equal to one several years before or after the year of approval t_0, indexed by time-to-treatment d (negative before the approval year and positive after). The dependent variable is the installed capacity density of photovoltaic installations in municipality i at year t (in kW per km^2). The coefficient of interest, β_d, captures the deviation from the parallel evolution in density of solar capacity between treatment and control groups d years after the adoption of a new land-use planning framework. Fixed effects are implemented at the municipality and region-time levels (indexed by subscript r) to control for any time invariant municipal characteristics, any changes over time that affect all municipalities, or specific to each region.

3.2 Threats to the identification

My empirical strategy involves several threats to the identification of a causal effect. I use alternative specifications and implement sensitivity analyses to address them.

Parallel trends. It is possible that the two groups follow diverging trends in the dependent variable if not receiving the treatment. This would violates the main assumption of DiD. I use a nearest neighbor matching between treated and controlled units given land-use patterns observed in 2012 at the municipality level (with the Corine Land Cover dataset) to verify the robustness of the parallel trends assumption. The nearest neighbor matching method pairs municipalities based on the similarity of their propensity scores of being treated calculated using the proportions of different land-use types within their territories. Land-use characteristics likely influence both the potential for solar development and a municipality's propensity to update its land-use planning framework. Hence reducing treated and control groups to subgroups with similar land-use patterns enhances the credibility that, absent the treatment, both groups would likely have exhibited comparable solar development trajectories. More details about the methodology are given in Appendix E. In an alternative specification, I also introduce socio-economic variables as time-varying covariates prior to the year of observation to verify if underlying socio-economic trends at the municipality level could bias the estimation.

Stable unit treatment validity assumption (SUTVA). The second main assumption for the DiD to be valid is that the treatment should have no interferences, or spillovers, on other units. In words, the adoption of a new land-use planning framework in a municipality should not impact the amount of land allocated to solar in neighboring ones. Specifically, my identification strategy could be affected a spillover of treated on controlled units. Under the assumption that solar PV developers prospect land only within a limited geographic area,[11] having stricter land-use regulation in one locality may attract solar developers to prospect

[11] Anecdotal evidence suggests that developers prospect land in large perimeters, typically within one regional administrative unit (12 regions in Metropolitan France). Indeed, main firms developing ground-mounted solar PV are often separated in regional branches.

land in neighboring localities with more permissive regulation. My estimation could also be affected by a spillover of treated on treated units. Still under the assumption that solar PV developers prospect land only within a limited geographic area, if a large part of the area adopts more restrictive regulation, developers may still need to site projects within these stricter jurisdictions to meet deployment targets. In such cases, the increased regulatory burden would likely be reflected in higher project costs, without necessarily deterring development. I check for spillovers in my setting by implementing a more restrictive matching strategy. I exclude all adjacent municipalities to the treated units, thus introducing a spatial buffer between treated and controlled groups, and verify if the estimation results change.

4 Data

I build a dataset that keeps track of when solar projects were commissioned at the municipality level and when a land-use planning framework was put in place in a municipality.

Universe of ground-mounted solar units. My first data source is a public registry listing the universe of power plants in France.[12] The dataset indicates where the solar units are located down to the municipality level, along with their installed capacity. The registry does not explicitly specify whether a given installation is a ground-mounted or a rooftop unit. Therefore, I assess whether each observation is a ground-mounted unit using different assignment strategies that are detailed in Appendix G.[13]

Land-use planning frameworks. My second data source is the list of land-use planning frameworks in place at the municipality level (*communes*)[14]. I observe the land-use planning framework in place for the year 2023 along with its date of approval. The dataset also

[12]https://www.data.gouv.fr/fr/datasets/registre-national-des-installations-de-production-et-de-stockage-delectricite-au-31-12-2022-2/, last accessed on 31 December 2023.

[13]Whether a given unit is ground-mounted is assessed based on (i) its name (when available), (ii) the prevailing size limits in technology-specific auctions, and (iii) geolocalized data on photovoltaic facilities retrieved from OpenStreetMap.

[14]https://www.data.gouv.fr/fr/datasets/planification-nationale-des-documents-durbanisme-plu-cc-plui-cc-rnu-donnees-sudocuh-dernier-etat-des-lieux-annuel-au-31-decembre-2022/, last accessed on 12 January 2023

indicates if municipalities are in the process of updating their land-use planning and to which type of framework. In order to have the history of former land-use planning frameworks, I retrieve the same data recorded in 2012, which corresponds to the oldest version available so far.[15]

Zoning rules. I retrieve cross-sectional data on latest land-use planning to date.[16] The dataset gives zonal maps with detailed land-use categories identified within the territory of about 60% of municipalities in metropolitan France.

Land-use cover. I constitute a fourth dataset depicting the proportions of land pertaining to different types of land-use. My main source is the Corine Land Cover (CLC) inventory.[17] CLC assigns 44 different types of land-uses at a 25 hectares precision using satellite images recognition. I use the cross-sections of 2012 and 2018, which corresponds to the beginning and the end of my period of study. I also nest the CLC items to around 15 broader categories differentiating between urban settlements, agricultural lands, natural spaces, wetland and coastal land. Table 10 in Appendix B displays the nested categories. CLC land-use items are completed with information on polluted and stranded industrial sites at the municipality level. This data is obtained by using the inventory of polluted sites (BASOL) and stranded industrial sites (BASIAS)[18].

Socio-economic characteristics. I use data on socio-economic trends at the municipality level taken from open-source datasets associated to Piketty and Cagé (2023). I focus on three key socio-economic characteristics at the municipality level. First, I retrieve timeseries on the average income per capita (before taxes). Second, timeseries on average properties value per capita, are the averaged value of housing observed on the real estate market.

[15] Some municipalities have been merged with others between 2012 and 2023 (around 1,500 units). To overcome this, I assign the older land-use planning framework of newly created (merged) municipalities by applying a pro-rata rule based on municipalities older status.

[16] accessed with https://www.geoportail-urbanisme.gouv.fr/api/

[17] https://www.statistiques.developpement-durable.gouv.fr/corine-land-cover-0, last accessed on 30 August 2023

[18] https://www.data.gouv.fr/fr/datasets/inventaire-des-sites-pollues/; https://www.georisques.gouv.fr/donnees/bases-de-donnees/sites-et-sols-pollues-ou-potentiellement-pollues, , last accessed on 30 August 2023

Third, timeseries on the average tax revenues per capita, comprise all local taxes raised by the municipality. The three variables are expressed as a ratio to their population means throughout the rest of the paper.

5 Descriptive analysis: where are ground-mounted solar installations?

This section presents the descriptive analysis drawn from the interaction of the location of ground-mounted solar installations with municipality level characteristics.

5.1 Ground-mounted solar and socio-demographic groups

Figure 2 displays the spatial distribution of ground-mounted solar installations crossed with the socio-demographic group of each municipality. In line with Piketty and Cagé (2023), I categorize municipalities in four groups. (1) Villages are municipalities of less than 2,000 inhabitants. (2) Towns are municipalities pertaining to urban areas of more than 2,000 inhabitants. (3) Suburbs are secondary municipalities of urban areas of more than 100,000 inhabitants. (4) Cities are municipalities that contain the city center of urban areas of more than 100,000 inhabitants.[19] Most installations seem to locate in towns or in villages that are close to urban areas. This is likely driven by more affordable rents when locating further away from city centers. Besides, most installations are in Southern parts of France. More particularly in the Rhône region, the Languedoc-Roussillon, and in Aquitaine. A substantial part of installations are also located in Northern France, despite lower solar irradiation levels.

5.2 Ground-mounted solar and land-use planning

Figure 3 displays the spatial distribution of ground-mounted solar installations crossed with the type of land-use planning framework in-use in 2023 at the municipality level. Most installations seem to locate in municipalities with a PLU or PLU-i. Graphs in Figure 4 provide further evidence of this steering. They display the distribution of projects (in number)

[19] Urban areas are defined by INSEE, accessible here: https://www.insee.fr/fr/information/4802589

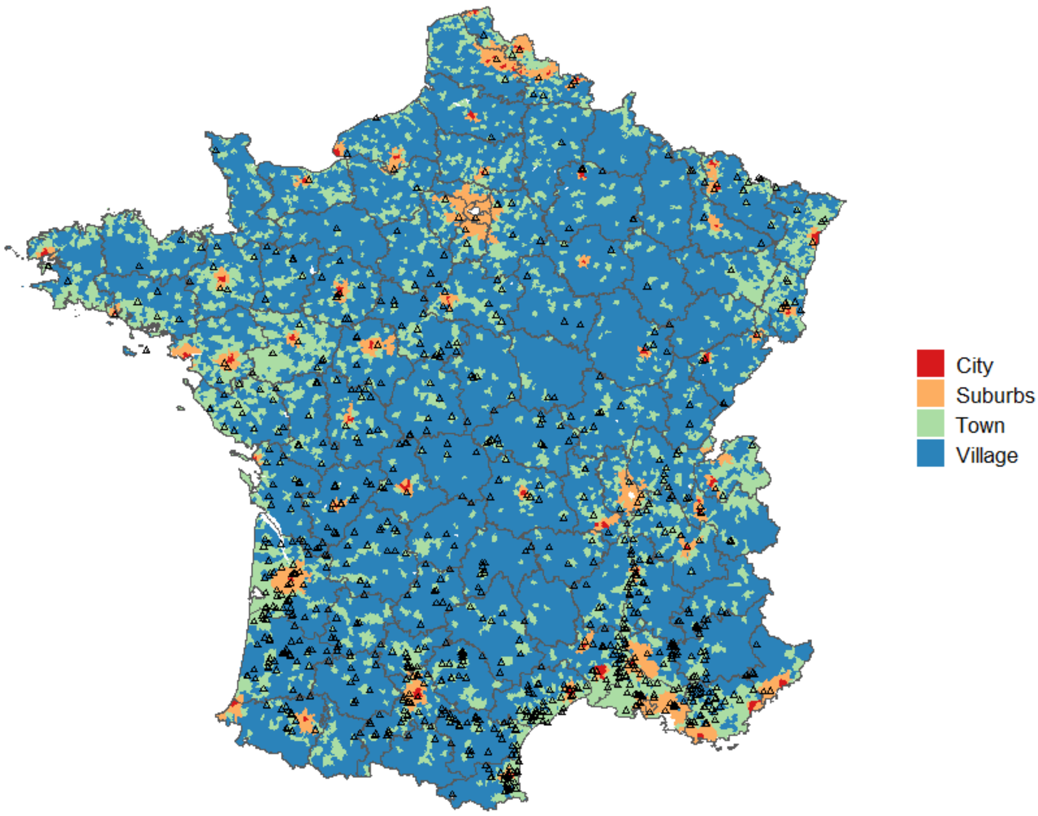

Figure 2: Map of ground-mounted solar facilities with socio-demographic groups of municipalities in 2023. Dark triangles are ground-mounted solar PV installations.
Notes: The three largest cities (Paris, Lyon, Marseille) are excluded from the data-set.

observed in 2023 across groups of municipalities. While 80% of installations are located in either a town or a village, a similar share of 80% is also in municipalities with a PLU or PLU-i. As shown by the bottom panel of the Figure, ground-mounted solar seem to particularly locate in the 50% share of villages equipped with a PLU or PLU-i. Moreover, when considering the land-use planning framework in place in 2012, a part of municipalities having solar installations in 2023 seem to have upgraded their land-use planning during the period.

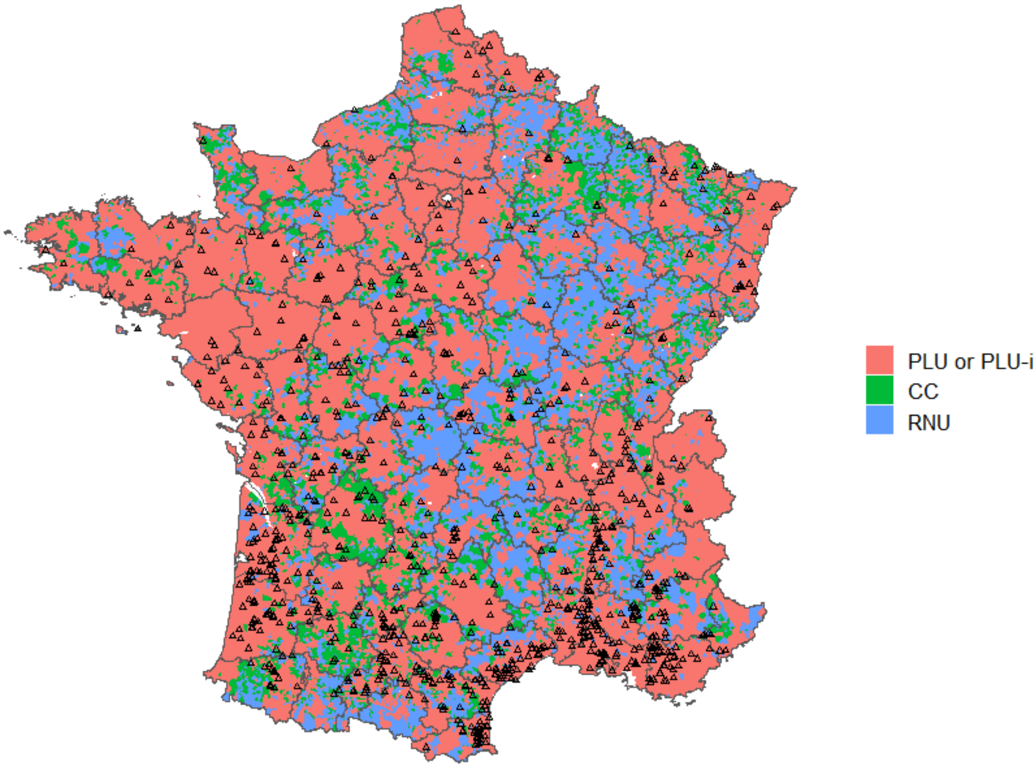

Figure 3: Map of ground-mounted solar facilities with types of land-use planning frameworks in 2023. Dark triangles are ground-mounted solar PV installations.

5.3 Ground-mounted solar and socio-economic variables

I investigate whether the uptake of ground-mounted solar is associated with key socio-economic characteristics at the municipality level. Using Piketty and Cagé (2023) datasets on socio-economic trends at the municipality level, I study the location of ground-mounted solar installations in relation to average income levels, property values, and local tax revenues of municipalities. Since most installations are located in towns and villages, I look at the distribution of projects within these subgroups only.[20]

[20]As displayed in Figures B.15 to B.17 in appendix, note that Villages and Towns are systematically pertaining to lower levels for each economic variable than Cities and Suburbs.

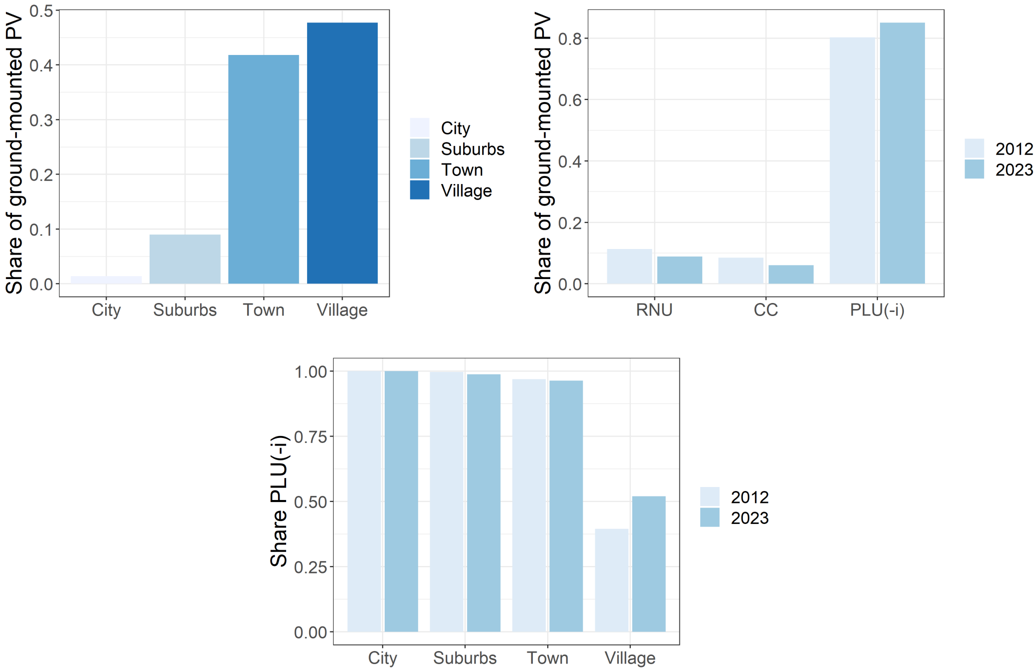

Figure 4: Distribution of ground-mounted solar installations observed in 2023 across municipalities (in number) by: socio-demographic group (top left panel); land-use planning in place in 2012 and in 2023 (top right panel); and land-use planning by group of municipalities in 2012 and in 2023 (bottom panel).

Figure 5 shows the share of ground-mounted installations that locate in each decile of the population of municipalities distributed by the three economic variables averaged across the four first years observed in the period (2008-2012). If there is no apparent correlation between ground-mounted solar and the economic variable we expect to have a 10% share of installations located in each decile, as marked by the horizontal line on the graph. We observe that there is a positive correlation of ground-mounted solar with average property value and with local tax revenues at the municipality level. Indeed, more installations are located in municipalities pertaining to the last deciles of these distributions. For example, about 50% of installations locate in the 30% municipalities with the highest local tax revenues. Considering income levels, ground-mounted solar seem more evenly distributed across median income levels of the distribution.

In Appendix C, I estimate the propensity of having ground-mounted solar relative to the

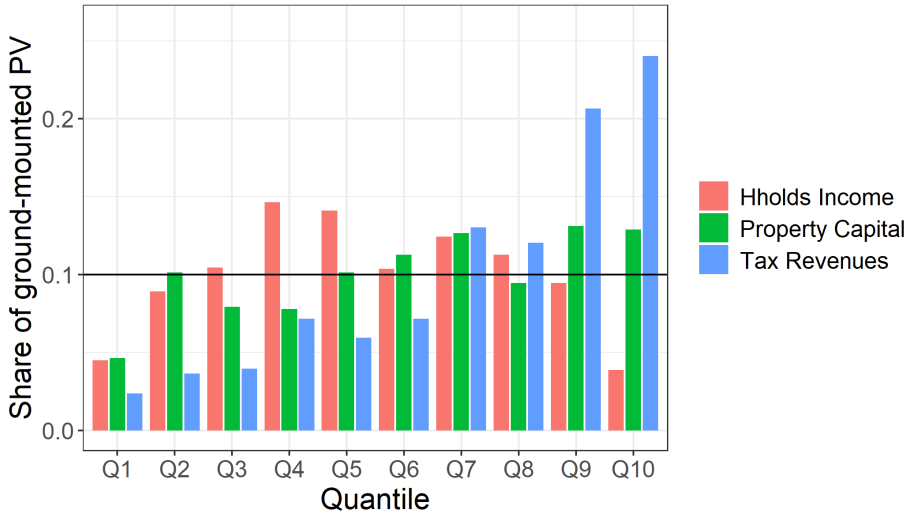

Figure 5: Share of ground-mounted solar installations in each deciles of Villages and Towns distributed by key economic variables.
Description of the variables: (1) average income per capita; (2) value of dwellings per capita; (3) taxes raised by the municipality per capita.

three economic variables with a logistic regression. I also introduce a dummy for having a PLU or PLU-i, and fixed effects at the socio-demographic group level. Results are displayed in Table 4 of Appendix C. Obtained coefficients are statistically significant and tell us that increasing the average property value level by one times its population mean increases the odds of having ground-mounted solar by 31%. A similar increase in average tax revenues increases the odds by 12%, and in average income levels decreases the odds by 70%. Conversely, having a PLU or PLU-i increase by 82% the odds of having ground-mounted solar.

5.4 Discussion

I draw several observations from this descriptive analysis. While being primarily located in towns and villages, utility-scale solar is not necessarily developed in areas with the lower property values nor lower income levels. Strikingly, the deployment of solar is positively correlated with local tax revenues observed at the beginning of the period. One could have expected solar to be incentivized to develop in localities with lower tax revenues, since they benefit more from additional revenues induced by its commissioning. Indeed, utility-scale solar is subject of several local tax impositions whose revenues fall on the municipality.[21] This steering can be explained by the characteristics of municipalities that can host utility-scale solar. It is likely that solar facilities are developed in priority near industrial areas, which already generate important local tax revenues. Indeed, developing solar near industrial zones alleviates disamenity costs onto residential dwellings and allows installations to site close to large end-consumers. Alternatively, this effect could also be linked to the characteristics of municipalities having more detailed land-use planning (PLU or PLU-i), entailing more land developments and thus higher average property value and local tax revenues.

6 Impact on ground-mounted solar permitting

I test weather different upgrades or updates of a land-use planning framework have an impact on the amount of land allocated to ground-mounted solar over the period 2012-2023. I investigate the impact of land-use planning frameworks in light of the mechanisms described in Section 2.4. I then run alternative specifications to test the robustness of my results.

6.1 Main results

Figures 6 to 8 display the coefficients of the regression and Table 8 in Appendix D provides the estimates. The outcome is the density of ground-mounted solar commissioned at the municipality level in kW per km^2. Using a rule of thumb of 1 hectare per MW, I can convert this value in m^2 of land per km^2 (Nøland et al., 2022). For each specification, I display two models: the first is computing the density of solar considering the whole municipality area, the second is considering only the area that is eligible to land developments in a municipality. I obtain shares of eligible land by summing up artificalized land cover at the municipality level observed at the end of the period (using CLC data observed in 2018). Figure C.21 displays the shares of eligible land observed at the municipality level. I only display estimation results with propensity score matching when parallel trends seem not valid

[21] Taxes on energy production revenues and land occupation (called CET), and specific flat tax on energy infrastructures (called IFER).

before treatment. Alternative models applying matching for all specifications are detailed in Appendix E.

(a) Effect of more detailed land-use planning. Figure 6 displays the coefficients for the impact of upgrading *RNU* or *CC* frameworks to a *PLU* framework on the density of ground-mounted solar. No coefficients before the year of treatment is significantly different from zero with and without propensity score matching (see Figure E.22). After the treatment, we observe an average increase in ground-mounted solar density starting from 4 years after the approval of the new land-use planning. The lag in the effect seems consistent with the average time for developing ground-mounted solar. Estimates have weak significance levels, being only statistically significant at the 90% level at the 4th and 8th year, and disappear after that date. Taking the outcome in density per area of eligible land improves statistical significance.

Table 8 in Appendix D provides estimates. On average, upgrading a less detailed land-use planning framework (*CC* or *RNU*) to a *PLU* framework increase the density of ground-mounted solar commissioned in the municipality by around 100 kW per km^2 of eligible land as compared to controlled municipalities, which is equivalent to an additional 1,000 m^2 per km^2, or 0.1% of the total amount of eligible land. Hence, *PLU* frameworks would unlock additional land for ground-mounted solar, confirming *proposition 1*. More detailed land-use planning frameworks identify greater amounts of land eligible to solar installations, due to better alignment with the national auctions' eligibility criteria.

(b) Effect of more recent land-use planning. Figure 7 displays the coefficients for the impact of updating a land-use planning framework after 2012 compared to municipalities with land-use planning frameworks approved before that date, and that are still in the process of updating it. In this specification, the treatment has only a significant effect when considering the density of solar per area eligible for new development. Estimates are not different from zero before treatment and we observe an overall significant effect on ground-mounted solar density starting from 4 years after the treatment at the 95% level. This suggests that treated units have fewer eligible areas for construction than the control group.

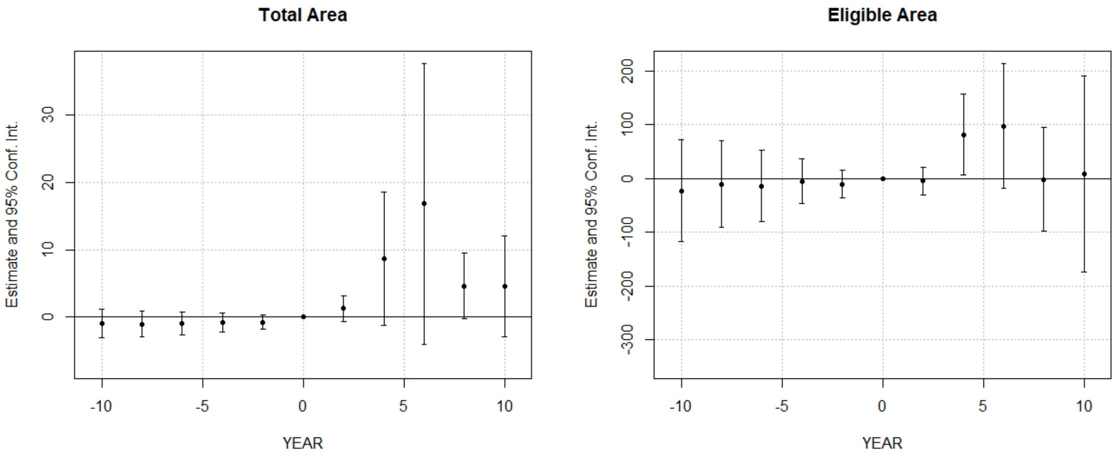

Figure 6: Estimates and 95% intervals from specification a). Left panel: density of solar computed with total area of municipality. Right panel: density computed taking only the area eligible for land developments (artificialized land observed in 2018).

Applying propensity score matching – to compare subgroups with more similar land-use patterns – does not alter the results

Table 8 in Appendix D provides the estimates. On average, updating a PLU after 2012 decreases the density of ground-mounted solar in the municipality by around -150 kW per km^2 from 4 to 10 years after the time of approval as compared to municipalities that have yet adopted a new PLU framework. This corresponds to an additional 0.15% of eligible land allocated to solar in controlled municipalities relative to treated ones. Hence, recent updates of land-use planning reduce the potential for ground-mounted solar at the municipality level which validates *proposition 2.* Municipalities with older frameworks identify more land available for development than their counterparts with more recent land-use planning.

(c) Effect of inter-municipal integration. Figure 8 displays the coefficients for the impact of integrating land-use planning frameworks at the inter-municipality level (PLU-i). Note that in this setting, treated municipalities originally have different land-use planning frameworks (RNU, CC or PLU) and that the elaboration of a PLU-i likely changes spatial planning for all constituent municipalities. Surprisingly, we observe a negative effect on ground-mounted solar density starting from 6 years after the treatment, which is statistically

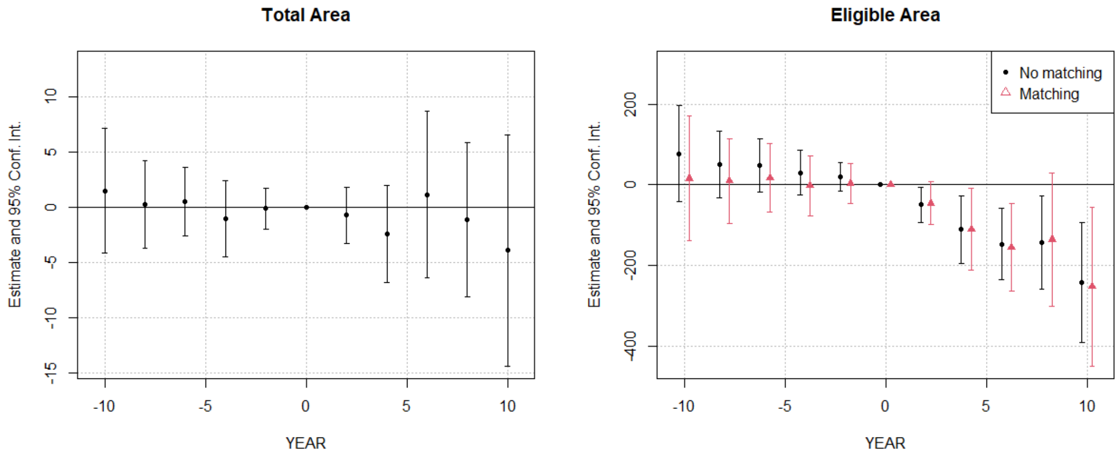

Figure 7: Estimates and 95% intervals from specification b). Left panel: density of solar computed with total area of municipality. Right panel: density computed taking only the area eligible for land developments (artificialized land observed in 2018).

significant at the 99% level.

Table 8 in Appendix D provides the estimates. Integrating land-use planning in a *PLU-i* decreases the density of ground-mounted solar in the municipality by an average of -100 kW per km^2, corresponding to a reduction in the allocation of around 0.1% of eligible land to solar relative to municipalities that have not yet integrated their land-use planning. Approving a *PLU-i* seems to reduce the potential for ground-mounted solar at the municipality level. This invalidates *proposition 3*. Potential drivers explaining this result are discussed in Section 7.

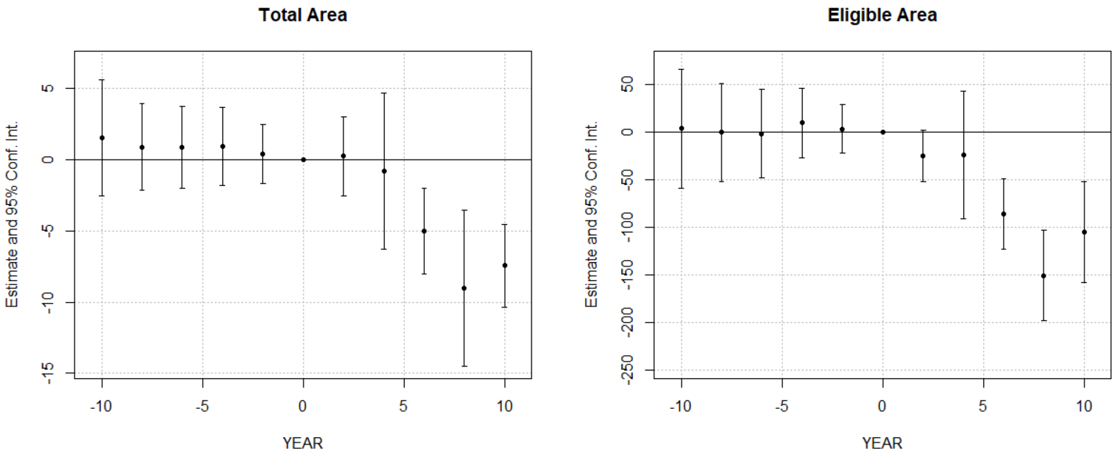

Figure 8: Estimates and 95% intervals from specification c). Left panel: density of solar computed with total area of municipality. Right panel: density computed taking only the area eligible for land developments (artificialized land observed in 2018).

6.2 Sensitivity analyses

6.2.1 Socio-economic covariates

A threat in the estimation is that the length of elaboration of a new land-use planning and therefore the year of treatment could be linked to time varying characteristics at the municipality level that are also correlated with the local development of solar. For example, it is possible that municipalities experiencing a lower economic growth take more time to approve their land-use planning and experience also less demand for new land takes in their jurisdiction, increasing the amount of land eligible to solar installations.

In this section, I include time-varying covariates in my specifications to account for potential trends in economic characteristics that could confound the impact. I choose the same variables as in Section 4, taken from data-sets of Piketty and Cagé (2023). All variables are reported at the municipality level and for the whole time window. They are averaged per capita and expressed as a ratio to the mean. Tables 5 to 7 in Appendix B, display statistics for each treated and controlled groups across my specifications. We see that, despite fixed differences, controlled and treated units follow very similar trends and small in magnitude. Treated municipalities pertain to higher income and property levels across all specifications.

Conversely, treated municipalities pertain to lower tax revenues levels for specifications (a) and (c). Therefore, municipality fixed effects should adequately control for these characteristics in the model. I conduct a sensitivity that confirm the robustness of this assumption. I introduce past socio-economic characteristics in my three specifications as lagged variables 4 to 6 years before the year of observation in order to be aligned with the length of permitting of solar facilities. Importantly, the three socio-economic covariates should be "good controls": adopting a new land-use planning framework should have no effect on properties' value, income levels or tax revenues at the municipality level. I verify this assumption in Appendix F.[22] Figure F.23 shows that upgrading a land-use planning framework impacts socio-economic trends by small magnitudes in specification (a) and (c). The effect seems particularly significant 10 years after the integration of a PLU-i (specification c).

The results of regressions after inclusion of time lagged socio-economic covariates are displayed in Figures 9. Overall, estimates are not changed in either sign or magnitude. The estimate of the effect of treatment 10 years after in specification (c) has lost in significance. This could be driven by reversed causality issues of land-use planning on socio-economic variables, since a "bad control" in specification (c).

6.2.2 Spillovers

In this section, I verify if my results hold after controlling for spillover effects. For example, having stricter land-use regulations in some localities could increase the amount of land allocated to solar PV in neighboring municipalities that did not update their land-use planning. This would occur because solar developers would be incentivized to move to these municipalities with relatively simpler permitting processes when prospecting land in a small geographical perimeter.

To verify the existence of spillovers, I introduce a spatial buffer between treated and controlled municipalities and estimate the effects of changes in land-use planning by studying differences in solar density between treated and controlled units that are more distant from

[22] I implement a similar Staggered difference-in-difference strategy where I replace the dependent variable by my socio-economic covariates.

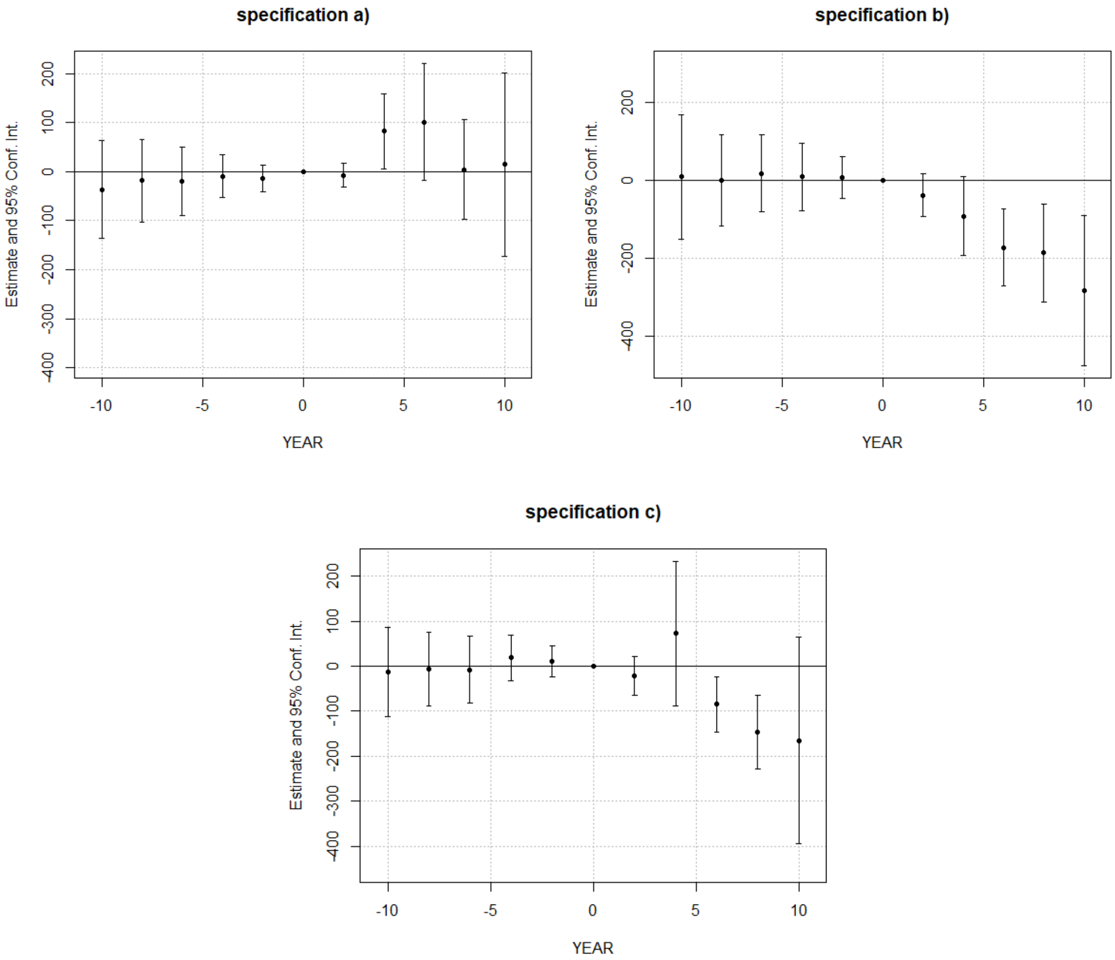

Figure 9: Estimates and 95% intervals when adding lagged time-varying covariates (4 to 6 years before time of observation) for specifications: (a) to (c). Outcome variable is in density per area of eligible land.

each other. This rules-out any effects that could stem from the direct proximity of a treated and a control unit, since the latter is no longer included in the DiD. I construct a matrix indicating all the adjacent municipalities to each unit of observation. Then, for each treated unit, I delete all its adjacent municipalities when pertaining to the control group. Figure 10 below displays the obtained coefficients. The estimates seem unchanged when controlling for treated on controlled units spillovers.

I use a similar approach to investigate the existence of treated on treated spillovers. Using the same weight matrix indicating adjacent municipalities, I delete all treated neighbors for each treated unit. However in this case, depending on the sequence, I do not end with the same sample of treated municipalities. I thus iterate the exercise by randomly reshuffling my set of treated units. Figure F.24 in Appendix displays the obtained coefficients in each specification after 5 iterations. Despite lowering the statistical significance of estimates, the sign and magnitude of the obtained coefficients seem not impacted by treated on treated spillovers for specifications (a) to (c).

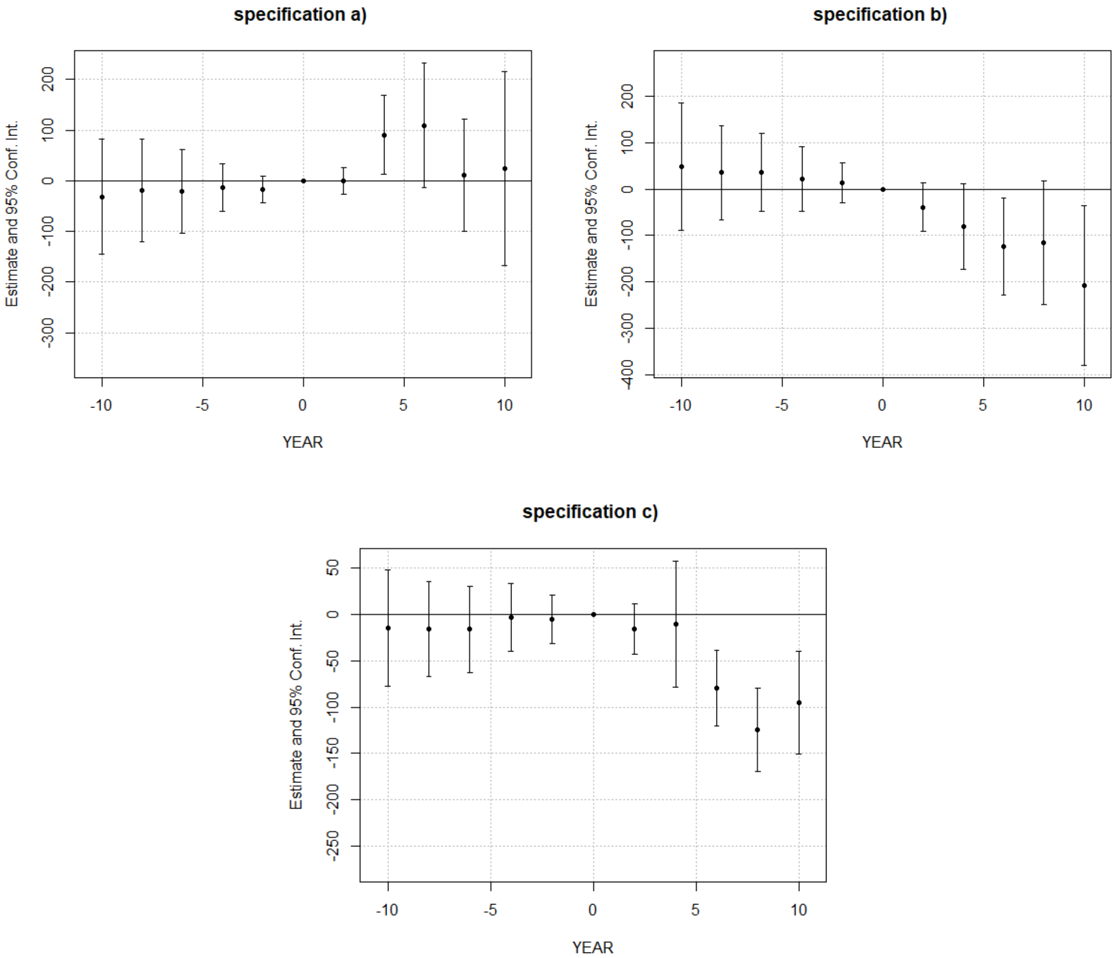

Figure 10: Estimates and 95% confidence intervals when removing municipalities adjacent to treated units in the control group. Outcome variable is in density per area of eligible land.

7 Discussion

I find two explanations for the obtained results. First, land-use regulations – eligibility criteria defined by the energy regulator translated in land-use planning – induce easier permitting for installations when located in municipalities under a detailed land-use planning framework, i.e. a PLU (specification (a)). Indeed, the PLU framework has more zoning categories to identify land developments that are in line with eligibility criteria set by the energy regulator. In contrast, land eligible for solar in a less detailed land use planning framework, such as the CC framework, is disadvantaged compared to if it were identified in a PLU. Additional administrative authorizations are required in the latter case on top of compliance with land-use planning, as detailed in Section 2.3.

Second, solar developers are led to focus primarily on land plots identified for new developments in PLU when prospecting for new projects. They have to compete with alternative construction projects and target the land with lowest possible costs. Hence, solar developers tend to site in localities that present less competition for new land developments. My findings suggest that such localities are municipalities with an old land-use planning framework (specification (b)), and municipalities that have not yet integrated their land-use planning at the inter-municipality level (specification (c)).

7.1 Mechanisms

While the first effect is well explained by the alignment of eligibility criteria in national public auctions with land-use planning frameworks, the second effect deserves closer investigation. There are three exploratory mechanisms to explain the land competition effect fund in specifications (b) and (c).

First, this effect can be driven by the gradual integration of land conservation objectives at the local level. Land-use planning frameworks approved earlier in the period have not yet incorporated land conservation objectives that were formalized in legislation later on. Indeed, we witnessed rapid evolution of legislation during last decades aiming to reduce land artificialization, as described in Section 2.2. Against this context, it is possible that municipalities reacted to increasingly formalized policy objectives on land conservation by reducing the quantity of land eligible for new development upon upgrades of their land-use planning frameworks.

To explore this mechanism I gather and use data on zoning at the municipality level. I access zonal maps with land use categories for the 60% of municipalities in metropolitan France that are under a PLU framework, which correspond to the latest update of their land-use planning to date. Although this only gives me a cross-sectional view of land-use planning regulations, I can investigate if quantities in different zoning categories change with the year of approval of the land-use planning framework. I implement an OLS regression to study the correlation between the year of approval of the framework with the share of land identified as eligible for new land developments, controlling for the socio-demographic group of the municipality (i.e. city, suburb, town or village). Results of the OLS are displayed in Table 2 below. I run two specifications, the first use the category that identifies already constructed land as outcome variable (Zone U), the other specification uses the category that identifies land available for new developments (zone AU). I find that a one year difference in the year of approval of the land-use planning framework reduces the amount of land available for new developments by 0.2%, while not impacting the quantity of land already built. The lack of correlation between the quantity of already constructed land and the time of approval deletes the concern that municipalities that approved land-use planning later in the period have already developed most of their buildings, leaving less land for new development. Nevertheless, we can have a bias stemming from older land-use planning frameworks that have registered older zonal maps in the data repository, which may not account for all latest land developments as compared to recent ones. Further research is needed on the investigation of land conservation adoption at the municipality level.

The second exploratory mechanism could be implied by changes in incentives for municipal authorities that have integrated their land-use planning regulation at the inter-municipality level. One can expect that land allocation in a jurisdiction occurs if there are net benefits for the locality (Fischel, 2004). Local benefits of designating a land plot

Table 2: OLS regression of eligible land on year of approval

	Dependent variable:	
	Zone U	Zone AU
	(1)	(2)
Intercept	128.31**	331.85***
	(53.24)	(11.88)
Suburbs	−18.37***	−0.25
	(2.78)	(0.62)
Town	−46.55***	−1.03*
	(2.75)	(0.61)
Village	−57.35***	−2.41***
	(2.75)	(0.61)
Year of Approval	−0.03	−0.16***
	(0.03)	(0.01)
Observations	8,697	8,696
R^2	0.45	0.14
Note:	*p<0.1; **p<0.05; ***p<0.01	

eligible for a solar installation are mainly specific local tax revenues, while costs are the loss of utility of local inhabitants affected by the conversion of nearby land. After integration at the inter-municipality level, the distribution of costs and benefits changes. While tax revenues are now shared within the inter-municipality, disamenity costs incurred by residents still fall on the municipal authority, through political backlash during subsequent municipal elections. Hence, municipalities that integrate an inter-municipality should have reduced incentives to designate land to renewable energy projects. Further research is needed to validate the existence of this channel.

The third exploratory mechanism is the inclusion of a new and additional planning tool that could be used by inter-municipalities to hinder the local development of renewables. Indeed, inter-municipalities can issue a local Climate Air Energy Plans (*PCAET*). *PCAETs* are planning document that given a list of actions and measures to be taken at the jurisdiction level to achieve environmental objectives in the next years. For example, *PCAETs* can set precise targets for the development of renewable energy technologies after identification of specific local potentials for their deployment. Conversely, these tools can also put more emphasis on biodiversity objectives and the preservation of natural spaces. Hence, the *PCAET* could be used to add more rules against on the development of solar installations. Since 2019, this planning tool became mandatory for all inter-municipalities larger than 20,000 inhabitants. Using this population threshold, I can explore the relevance of this mechanism by estimating the impact of upgrading to a PLU-i framework conditionally of being above or below a population of 20,000 inhabitants. Results are displayed in Figure 11. We observe that effect of integration for municipalities above the threshold on ground-mounted solar is higher in magnitude than the one for municipalities below. This result indicates that *PACET* could indeed be used by municipalities to oppose the local commissioning of solar, following a NIMBYism effect. This calls for further research to investigate how *PACET* are elaborated and implemented in localities.

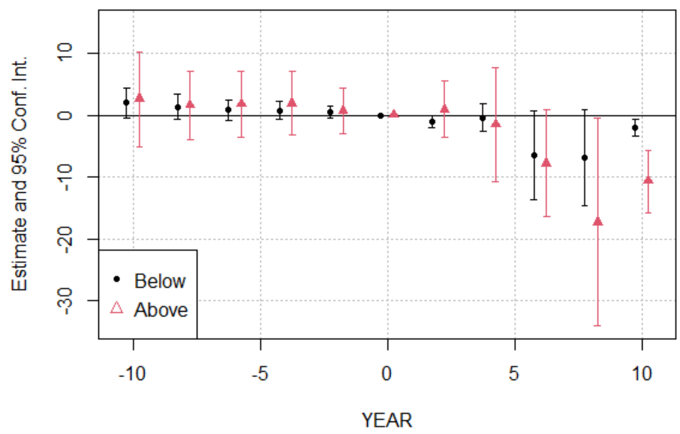

Figure 11: Estimates of specification c) conditional on having municipalities above or below the population threshold.

7.2 Policy implications

This paper has two main policy implications. First, I show that there can be coordination issues among jurisdictions when implementing regulation, possibly leading to an inefficient spatial deployment of solar.[23] I refer to such phenomenon as *policy implementation failures*, which are of two types. First, there is a *static* implementation failure between the national energy regulator and local authorities. Eligibility criteria in national energy auctions are not adapted to the variety of land-use planning frameworks at the local level. They are well aligned with zoning categories available in detailed land-use planning frameworks, but they cannot apply similar allow ban rules to less detailed frameworks, necessitating additional assessments to ensure compliance. This, in turn, increases the length and costs of permitting solar facilities in a significant part of the French territory, and eventually decreases the quantity of land allocated to solar. Applying a rule of thumb, I get that having all municipalities at the *PLU* framework would unlock an additional 0.5 GW capacity deployed on the territory.[24] This is equivalent to the total capacity procured by national energy auctions in

[23]An evaluation of such distortions is left for further research. This would first require having a valid counterfactual of current land-use regulations and a comprehensive analysis of local costs and benefits generated by the siting of ground-mounted solar installations.

[24]To get this result, I retrieve the total amount of eligible land in all municipalities under the RNU and CC frameworks (4500 km^2) and multiply by the average point estimate in specification (a) (100 kW/km^2)

2015. Hence, this paper advocates for changing the design of eligibility criteria in national energy auctions. For example, setting rules that are only based on evaluations by expertise authorities on project location conditions, regardless of the specific land use planning framework in place, could ensure more equitable treatment of projects in different local regulatory frameworks.

Second, there is a *dynamic* implementation failure of land-use regulation among local jurisdictions. Given the staggered adoption of land-use planning frameworks across local jurisdictions – due to the absence of mandated deadlines and lengthy administrative procedures – there are temporal disparities in the implementation of new legislation at the local level. These disparities can lead to distortions in the spatial deployment of solar. Specifically, solar installations are steered towards localities that have yet updated their regulatory frameworks, being less restrictive for land developments. Mandating frequent land-use planning renewals and establishing deadlines in the elaboration process could mitigate these effects.

The second main implication of this work pertains to governance challenges in solar energy deployment. Recent literature outlines that divergent interests between local and national authorities can lead to an inefficient decentralization of support policies for the deployment of renewable energy (Meier and Lehmann, 2022).[25] My findings support this empirically. I show that the transfer of planning responsibilities to local authorities can result in an inefficient outcome, where only local preferences are internalized in decisions. In my context, local Climate Air Energy Plans (PCAET) could be used to tradeoffs renewable energy deployment with environmental amenities. Second, at a more local scale, my findings suggest that incentives to allocate land to solar can be reduced after changes of tax bases due to integration at the inter-municipality level. The dilution of local tax revenues among jurisdictions of the inter-municipality may reduce the net benefits of a local jurisdiction to

[25] This analysis has given rebirth to a long-lived debate on the optimal allocation of responsibilities for regulating an environmental good, addressed by the fiscal and environmental federalism literature (Oates, 1999; Agrawal et al., 2024). Literature has notably shown that in the presence of spillovers upon the provision of a public good – typically climate mitigation or air pollution control – strategic interactions between local jurisdictions can result in an inefficient outcome, where localities under-provide the good to avoid bearing the local costs of its allocation (Besley and Coate, 2003).

allocate land to solar facilities. This is true given the occurrence of high disamenity costs stemming from solar development. These local costs are still incurred by municipalities in subsequent local elections. Against this issue, this paper advocates for targeting the allocation of the specific tax revenues of renewable energy to jurisdictions that best match local voters' preferences.

8 Conclusion

How does land-use regulation impact the spatial deployment of utility-scale solar installations? Sound policy instruments to identify and target suitable land for sitting renewable energy facilities are critical to achieve an effective roll-out. However, the decentralization of land-use regulation can lead to imperfections upon their implementation.

This paper demonstrates that issue by investigating the impact of joint regulation – between top and local administrative levels – on the spatial deployment of solar in France. Using a quasi-experiment, I outline different sources of policy implementation failures due to the fragmentation of land-use planning at the municipality level. First, I show that the heterogeneity of regulatory frameworks to establish land-use planning at the local level change the translation of top-level regulation for sitting solar facilities. More detailed land-use planning frameworks are better aligned with top-level regulation and can target more land eligible to the development of solar installations. Second, I show that recently approved land-use planning frameworks reduce the amount of land eligible to solar due to more stringent land-use regulations, which is likely driven by the heterogeneous and lagged formalization of land conservation policies at the local level. Third, I show that changes in local incentives upon integration at the inter-municipality level reduce the amount of land allocated to solar. More research is needed to assess such distortions and to investigate the efficiency conditions of alternative policy instruments and institutional settings.

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A Supplementary Figures

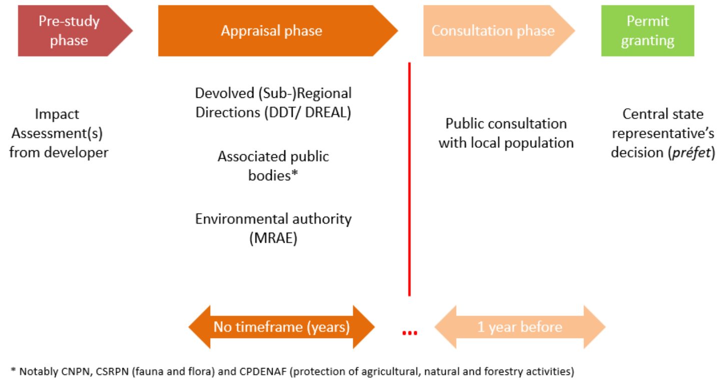

Figure A.12: Process for permitting ground-mounted solar PV, adapted from France Territoire Solaire (2021).

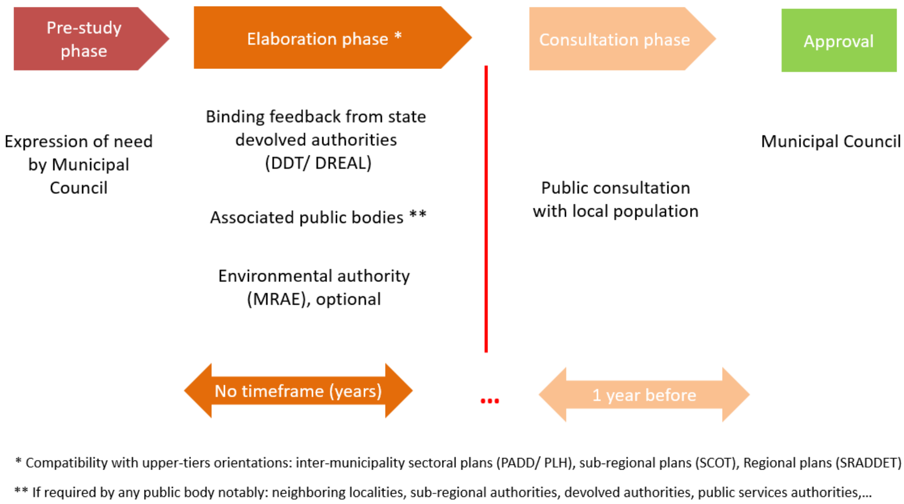

Figure A.13: Process for elaborating land-use planning, Code de l'Urbanisme, 2023.

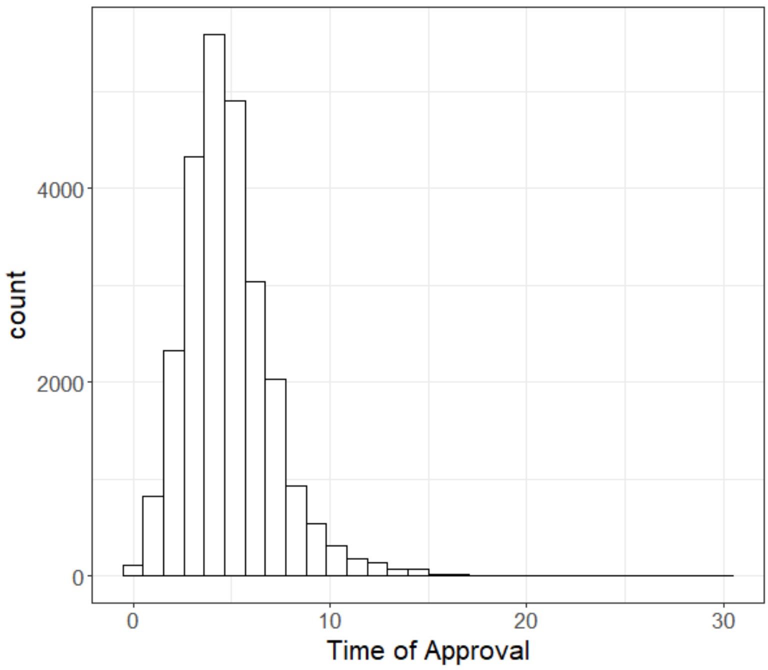

Figure A.14: Histogram of time duration between start of elaboration and approval of land-use planning frameworks.

B Descriptive statistics

B.1 Statistics at regional level

Table 3: Statistics at the regional level

Region code	Munici-palities	Ground-mounted PV (GW)	Share PLU(-i) in 2023	Share PLU(-i) in 2012	Year Approbation Q20	Year Approbation Q80
11	1,267	0.16	0.88	0.08	2012	2020
24	1,757	0.51	0.73	0.41	2010	2021
27	3,698	0.36	0.43	0.17	2008	2020
28	2,679	0.07	0.62	0.32	2010	2020
32	3,764	0.26	0.70	0.36	2011	2020
44	5,122	0.69	0.50	0.13	2007	2019
52	1,220	0.35	0.90	0.42	2011	2021
53	1,215	0.08	0.83	0.29	2009	2020
75	4,305	2.63	0.66	0.30	2009	2020
76	4,456	1.54	0.59	0.17	2008	2020
84	4,024	0.78	0.64	0.17	2009	2020
93	945	1.50	0.78	0.09	2011	2019

Notes: Shares are in terms of surface area. Year Approbation stems from the year of approval of land-use planning frameworks, where Quantiles 20 and 80 are reported.
Region codes: "11" = *Ile-de-France*, "24" = *Centre-Val de Loire*, "27" = *Bourgogne-Franche-Comté*, "28" = *Normandie*, "32' = *Nord-Pas-de-Calais-Picardie*, "44" = *Grand Est*, "52" = *Pays de la Loire*, "76" = *Occitanie*, "53" = *Bretagne*, "75" = *Nouvelle Aquitaine*, "93' = *Provence-Alpes-Côte d'Azur*, "84" = *Auvergne-Rhone-Alpes.*

B.2 Socio-economic characteristics

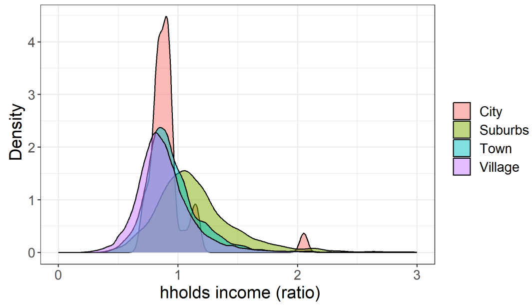

Figure B.15: Distribution of municipalities in function of average households income levels observed in 2019–2022.

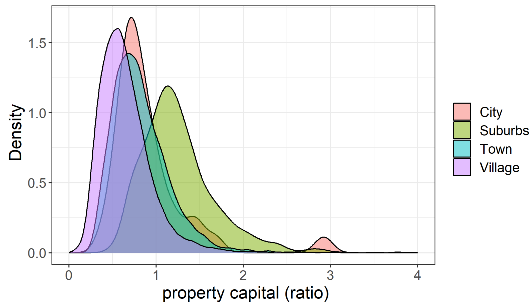

Figure B.16: Distribution of municipalities in function of average property value levels observed in 2019–2022.

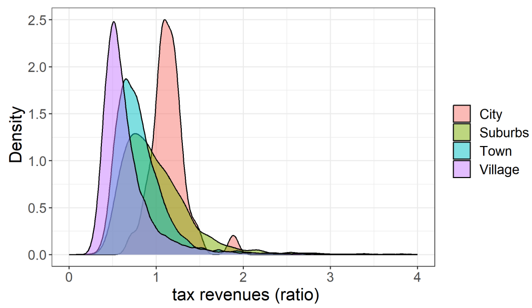

Figure B.17: Distribution of municipalities in function of tax revenues value levels observed in 2019–2022.

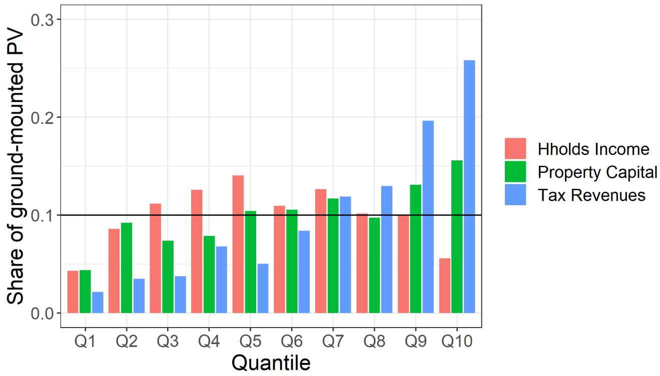

Figure B.18: Share of ground-mounted solar in each deciles of municipalities in function of economic variables, levels observed in 2008–2011.

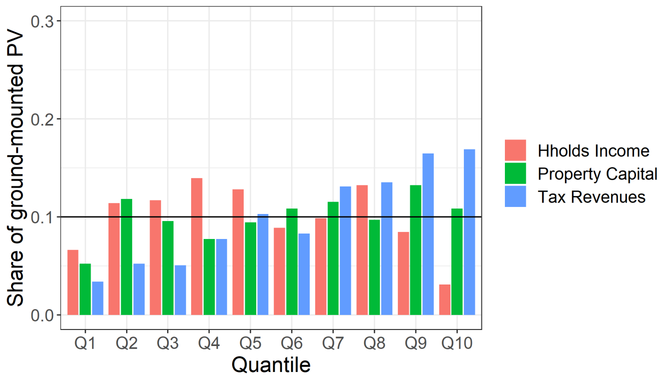

Figure B.19: Share of ground-mounted solar in each deciles of Villages in function of economic variables, levels observed in 2008–2011.

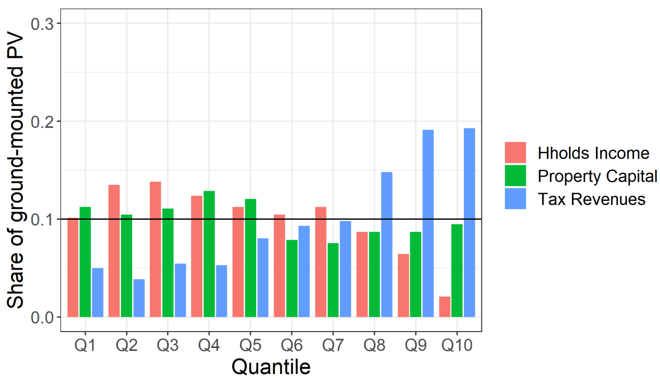

Figure B.20: Share of ground-mounted solar in each deciles of Towns in function of economic variables, levels observed in 2008–2011.

Table 4: Logistic regression: propensity of hosting solar on socio-economic characteristics at the municipality level

	Ground-mounted solar
PLU or PLU-i	0.67^{***}
	(0.133)
Income	-1.18^{***}
	(0.178)
Property	0.27^{**}
	(0.114)
Tax revenues	0.11^{***}
	(0.029)
Constant	-0.98^{**}
	(0.451)
Category Fixed Effects	Yes
Observations	33,932
Log Likelihood	−4,010.631
Akaike Inf. Crit.	8,039.262

*p<0.1; **p<0.05; ***p<0.01

Notes: Income, tax revenues and property value are expressed per capita and as a ratio to their population's mean.

B.3 Balancing of covariates in econometric specifications

Table 5: Statistics for specification (a), without matching

	Control	Treated
Municipalities	5,823	5,204
incl. Villages	5,800	5,105
Income		
	0.820	0.847
	(0.168)	(0.159)
	[-0.000]	[-0.000]
Tax		
	0.670	0.648
	(0.456)	(0.526)
	[0.001]	[0.001]
Property		
	0.608	0.673
	(0.266)	(0.267)
	[-0.005]	[-0.005]

Notes: Averaged levels for the period 2008–2012. Standard deviations are reported in (parenthesis) and [brackets] give annual trends, being the average change per year over the studied period (2010–2022). Income, tax revenues and property value are expressed per capita and as a ratio to their population's mean.

Table 6: Statistics for specification (b), without matching

	Control	Treated
Municipalities	2,722	4,952
incl. Villages	1,858	2,756
Income		
	0.934	0.979
	(0.229)	(0.223)
	[0.000]	[0.001]
Tax		
	0.761	0.772
	(0.658)	(0.541)
	[0.001]	[0.000]
Property		
	0.800	0.910
	(0.328)	(0.357)
	[-0.004]	[-0.004]

Notes: Averaged levels for the period 2008–2012. Standard deviations are reported in (parenthesis) and [brackets] give annual trends, being the average change per year over the studied period (2010–2022). Income, tax revenues and property value are expressed per capita and as a ratio to their population's mean.

Table 7: Statistics for specification (c), without matching

	Control	Treated
Municipalities	9,114	6,221
incl. Villages	7,992	5,190
Income		
	0.879	0.891
	(0.195)	(0.188)
	[-0.000]	[0.000]
Tax		
	0.700	0.688
	(0.511)	(0.390)
	[0.000]	[0.000]
Property		
	0.686	0.740
	(0.286)	(0.325)
	[-0.005]	[-0.005]

Notes: Averaged levels for the period 2008–2012. Standard deviations are reported in (parenthesis) and [brackets] give annual trends, being the average change per year over the studied period (2010–2022). Income, tax revenues and property value are expressed per capita and as a ratio to their population's mean.

C Eligible land in 2018

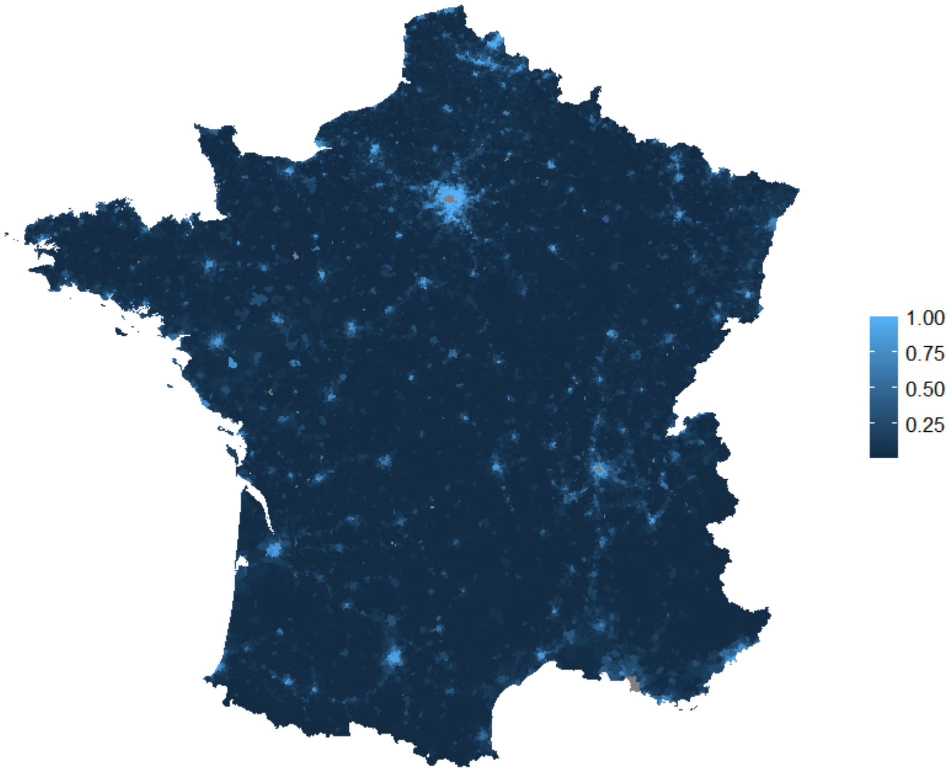

Figure C.21: Shares of land artificalized in 2018 at municipality level. Artificalized land cover correspond to nested categories CLC_{111} to CLC_{14} in Table 10 of Appendix E.

D Table of estimates

General notes on the table: The following table of estimates corresponds to specifications (a) to (c) with the outcome variable expressed in capacity per area of land artificialized at the end of the period (deemed eligible for solar). For specfiication b) estimates obtained in the model using propensity score matching are displayed.

Table 8: Table of estimates for the main results' specifications

	Ground-mounted solar (in kW per km^2 of eligible land)		
Specification:	(a)	(b)	(c)
YEAR = -10	-15.1	15.7	5.50
	(46.7)	(79.1)	(31.4)
YEAR = -8	-2.66	9.27	-6.40
	(39.7)	(53.6)	(25.7)
YEAR = -6	-4.51	16.8	-10.0
	(33.1)	(43.1)	(23.9)
YEAR = -4	6.68	-2.18	5.26
	(21.9)	(37.6)	(18.7)
YEAR = -2	-4.58	3.26	1.28
	(13.3)	(25.2)	(12.0)
YEAR = 2	-0.507	-46.0*	-20.0*
	(14.7)	(27.2)	(11.0)
YEAR = 4	99.6**	-110.4**	-25.9
	(45.4)	(51.9)	(25.6)
YEAR = 6	118.7*	-155.9***	-77.4***
	(67.5)	(55.3)	(15.4)
YEAR = 8	-3.18	-135.7	-126.3***
	(47.4)	(84.0)	(21.1)
YEAR = 10	8.41	-252.8**	-105.1***
	(92.9)	(100.2)	(27.1)
Fixed Effects	Yes	Yes	Yes
Observations	153,958	76,188	210,364
R^2	0.57852	0.65995	0.51016
Within R^2	0.00082	0.00092	0.00035

Clustered (Municipality) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

E Propensity Score Matching

Matching consists in selecting beforehand a subset of units in control and treated groups that are "most alike" conditional on baseline covariates to reduce selection bias in the estimation. I use a *one-on-one nearest neighbor matching* approach based on propensity scores to balance my treatment and control groups. Specifically, I match all units of the smallest group to their closest counterparts in the largest group. The approach estimates the propensity score of being treated conditional on baseline variables that are likely omitted variables in the estimation. I use land-use cover at the municipality level given by the Corine Land Cover dataset in the year 2012 (see Section 4). Land use categories are nested according to Table 10 to avoid empty variables across all municipalities in a subgroup while maintaining a sufficient level of detail. I add two additional variables depicting the share of land occupied by old, stranded and polluted sites.[26] Under current regulation, this type of land is prioritized for sitting ground-mounted solar installations. I also add the density of population of the municipality, the proportion of detached houses versus apartments and the proportion of secondary residences observed in 2012. Finally, a dummy variable indicates if the unit is in one of the four Southern regions in metropolitan France.

Results of Logit regressions estimating the probability of being treated conditionally to the three main specifications are displayed in Table 9 . The fifth column of Table 9 shows a similar regression when studying the presence of ground-mounted solar installations instead.

[26]This data is taken from national registries BASOL and BASIAS, more details in Section **??**

Table 9: Logit regression for the three specifications and ground-mounted solar

	(a)	(c)	(b)	(PV)
Basias	152.223*	15.130	−3.009	22.844***
	(89.940)	(10.854)	(5.699)	(8.279)
Basol	−8.246	3.683	−2.853*	1.227
	(9.653)	(2.363)	(1.489)	(2.490)
CLC_111	242.010	3.871**	0.525	4.123*
	(654.693)	(1.637)	(1.189)	(2.496)
CLC_112	−2.295	1.986***	0.692	−2.483***
	(1.413)	(0.694)	(0.497)	(0.918)
CLC_121	13.505***	1.405	0.640	5.329***
	(4.355)	(0.888)	(0.647)	(1.084)
CLC_123	5.273*	1.208	−0.281	0.869
	(2.709)	(1.191)	(0.942)	(1.472)
CLC_13	6.595**	5.712***	0.710	9.816***
	(3.253)	(1.900)	(1.387)	(1.862)
CLC_14	4.979	0.543	−0.106	1.554
	(3.853)	(1.284)	(0.902)	(1.730)
CLC_21	1.658	1.256**	−0.613	−2.427***
	(1.104)	(0.632)	(0.459)	(0.765)
CLC_22	1.453	−0.133	0.805*	−1.366*
	(1.136)	(0.670)	(0.481)	(0.789)
CLC_24	0.640	0.502	−0.133	−2.410***
	(1.104)	(0.634)	(0.460)	(0.766)
CLC_31	1.027	1.023	−0.540	−2.476***
	(1.107)	(0.637)	(0.462)	(0.767)
CLC_32	1.389	1.188*	0.545	−0.170
	(1.120)	(0.659)	(0.485)	(0.785)
I(Region)	0.274***	0.039	0.025	1.613***
	(0.046)	(0.040)	(0.036)	(0.085)
Pop. density	0.695***	−0.163***	−0.002	−0.672***
	(0.066)	(0.033)	(0.026)	(0.120)
Houses	−0.065	−0.493***	−0.379***	−2.207***
	(0.350)	(0.183)	(0.134)	(0.267)
2ndary	0.035	−0.447***	−0.652***	−4.064***
	(0.187)	(0.145)	(0.138)	(0.334)
Observations	11,027	15,333	17,719	34,452
Log Likelihood	−7,398.281	−10,233.880	−11,836.460	−3,854.915

*p<0.1; **p<0.05; ***p<0.01

Notes: Only significant variables are displayed

Table 10: Nested categories taken from Corine Land Cover (2012)

Nested category	Description	Corine Land Cover
CLC_111	Urban environment (continuous)	CLC_111
CLC_112	Urban environment (discontinuous)	CLC_112
CLC_121	Enterprises zone	CLC_121
CLC_122	Transportation infrastructures	CLC_122
CLC_123	Ports and airports	CLC_123
CLC_13	Landfills, mines, worksites	CLC_131 to 133
CLC_14	Green spaces (urban)	CLC_141 to 142
CLC_21	Agricultural fields	CLC_211 to 213
CLC_22	Vegetables farming	CLC_221 to 223
CLC_24	Agricultural others	CLC_231 to 244
CLC_31	Forests	CLC_311 to 313
CLC_32	Prairies	CLC_321 to 333
CLC_335	Glaciers	CLC_335
CLC_334	Fire zones	CLC_334
CLC_4	Humid land	CLC_411 to 423
CLC_5	Coastal land	CLC_511 to 523

Matching caliper. I test the robustness of my results to propensity score matching with a caliper, being the maximum difference in propensity scores that is allowed to define a pair. Any pair with a score difference under that threshold is discarded from the final sample. I choose a caliper of 0.2, which is approximately the standard deviation of propensity scores across my specifications.

Figures E.22 below display the estimates obtained in each specification when using a caliper. Overall, results remain unchanged. Nonetheless, magnitudes of obtained estimates in specification (a) are decreased to -5 kW per m^2.

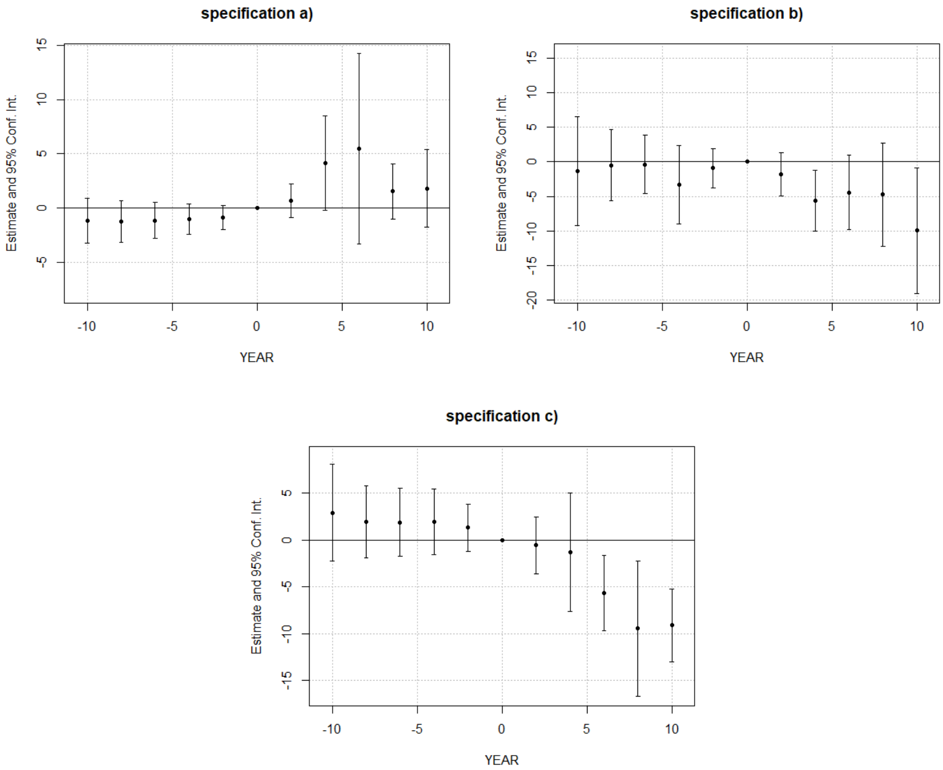

Figure E.22: Regression estimates with a matching caliper of 0.2.

F Other robustness checks

F.1 Effect on time-varying economic trends

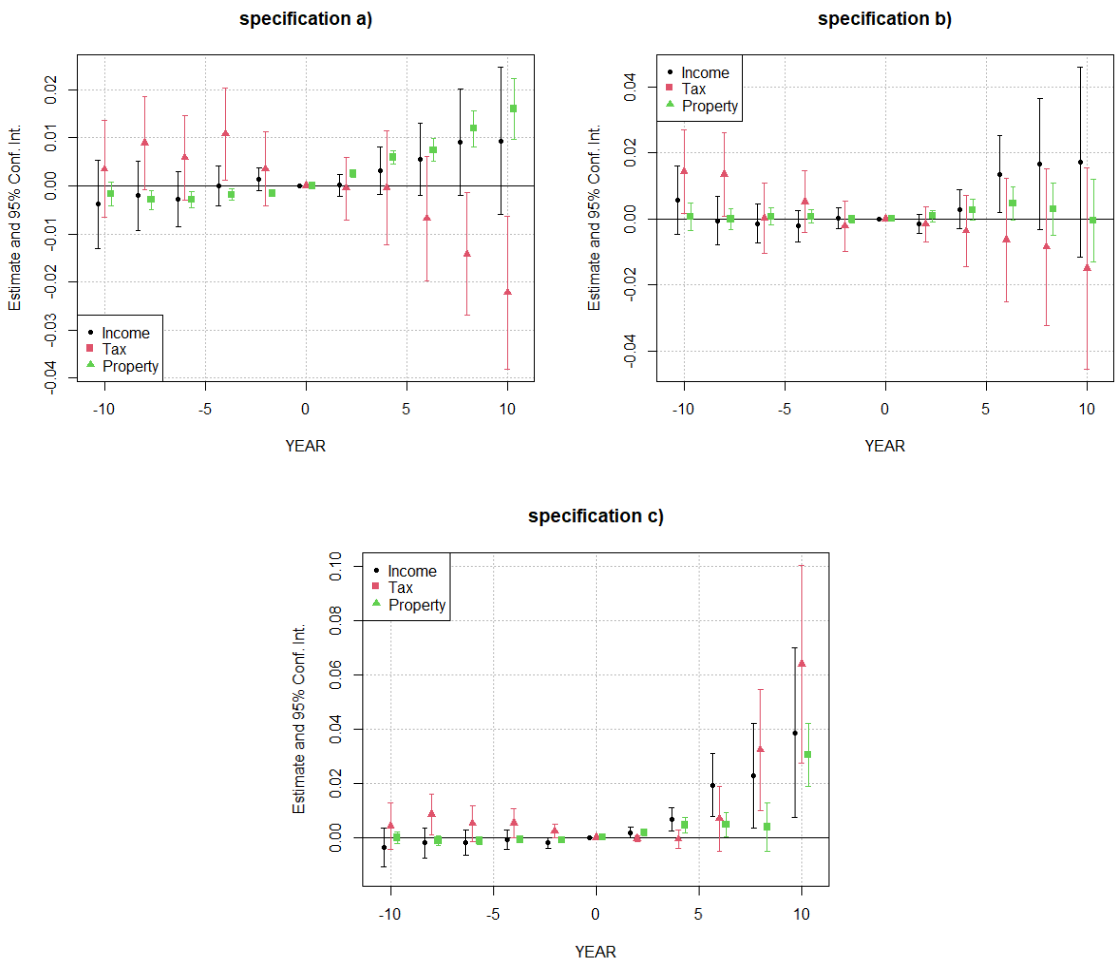

Figure F.23: Estimates and 95% intervals from staggered difference-in-differences for the impact of land-use planning upgrades on lagged time-varying covariates for specifications (a) to (c)

F.2 Treated-on-treated spillovers

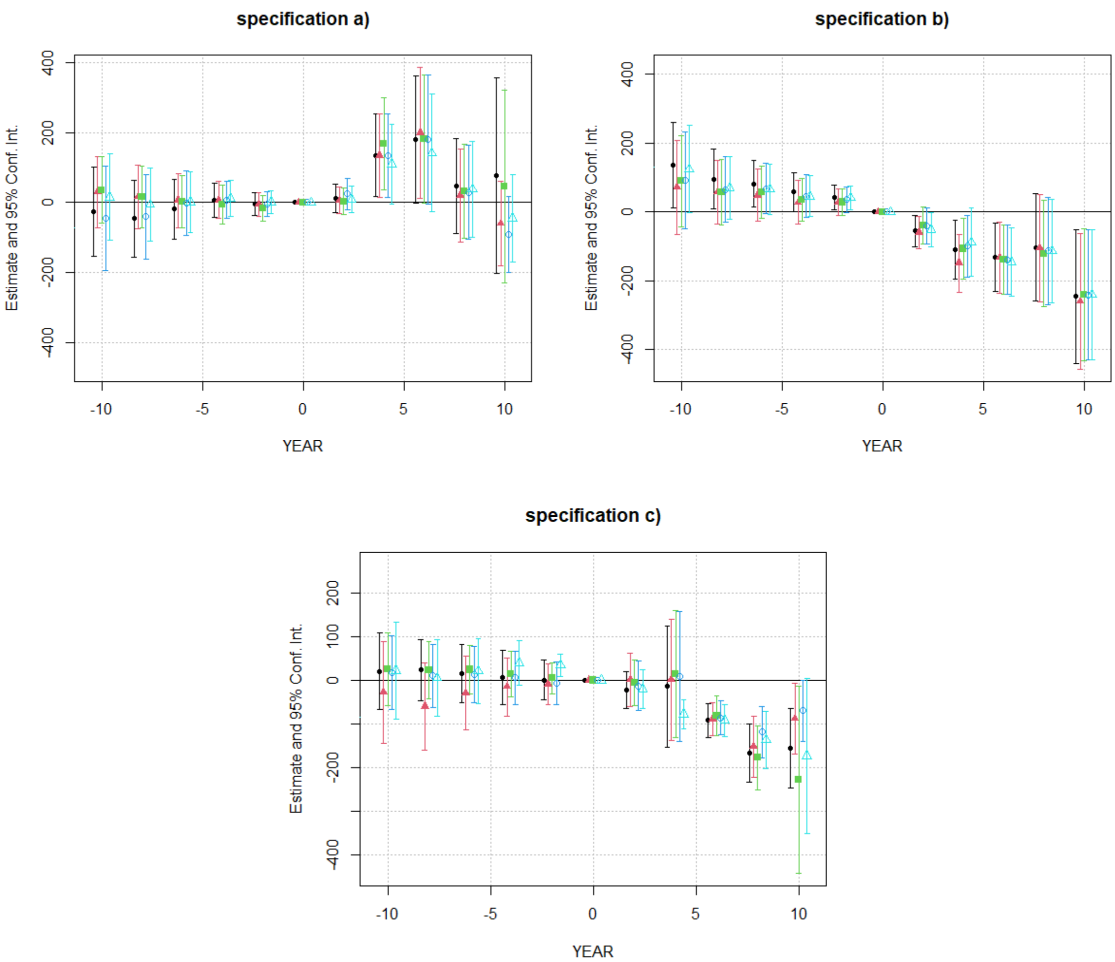

Figure F.24: Estimates when removing municipalities adjacent to treated units in the treatment group, Random shuffling of treated units in 5 iterations. Outcome variable is in density per area of eligible land.

G Details on the public inventory of ground-mounted solar installations

This Appendix details the steps implemented to assign large scale solar units ($>$ 500 kWc) to either ground-mounted or rooftop project types. The public inventory of power plants does not specify if a given unit is ground-mounted or rooftop. Four strategies are implemented to assign PV facilities to either rooftop or ground-mounted types, as detailed in the paragraphs below.

Size thresholds

The first strategy is to define size thresholds for each type of solar installation (rooftop or ground-mounted) by using the eligibility rules of support mechanisms and stylized facts. I am able to define three thresholds:

- There are no ground-mounted solar under 500 kW. Indeed, CRE auctions are only for projects larger than 500 kW.
- Solar energy auctions before 2016 set a maximum size for rooftop projects at 4.5 MW. I therefore assume that all units above 4.5 MW and installed between 2012 and 2017 (using one year construction lag) are ground-mounted.
- Auctions after 2016 have extended the size limit for rooftop PV to 8 MW. After 2017, only units larger than 8 MW are therefore automatically assigned to being ground-mounted.

This strategy allows me to assign 400 units to ground-mounted types.

Dictionary of key words in installations' names

The second strategy used to identify project types is to match installation names with a dictionary. I use the following key words:

- Words specific to rooftop installations: PARKING; PKG; OMBRIERE; TOITURE; SCI

- Words specific to buildings: SERRE; LOGISTIQUE; TECHNOPOL; LA POSTE; CENTRE COMMERCIAL; CENTRE; SAINT CHARLES; UNIVERSITE; ENTREPOT; STATION; HIPPODROME ;STADE; RESERVOIR; ARENA; OMNISPORT ;LYCEE; ETABLISSEMENT; CASERNE; HANGAR; USINE ;ZAC; SIEGE SOCIAL; BATIMENT; BAT; AEROPORT; STADE; STADIUM; CINEMA; SUPERMARCHE
- Words specific to large retailers and firms: CASINO; AUCHAN; GEANT; SANOFI; GIFI; SISLEY; IKEA; UBISOFT; LEROY MERLIN; RENAULT; LECLERC; CARREFOUR; SUPER U; SYSTEME U; HYPER U
- Words specific to ground-mounted installations: FERME SOLAIRE; CENTRALE; PARC SOLAIRE; CHAMP; AU SOL
- Known project names for ground-mounted projects: GABOTS; LAVANSOL; SOLAIREISTRES; ENFINITY; KRONOSOL; PLAINES; QUINCIEUX; TSAOS4.7; SALAUNES

This strategy allows me to assign about 40 units to ground-mounted types.

Auction winners

In the third strategy, I retrieve the list of winners from ground-mounted specific auctions and match the candidates names to the installations names in the inventory.

This method only identifies about 20 additional ground-mounted installations.

OpenStreetMap facilities

In the fourth strategy, I combine the list of solar units in the inventory with the list of solar installations that are reported in OpenStreetMap (OSM). OSM is an open-source database that stores geographic objects worldwide, including PV installations. OSM reports more than 1,300 PV installations that are located in mainland France[27]. As OSM focuses on spatial objects with significant land footprints, the majority of PV installations identified in the database are ground-mounted facilities. Rooftop installations listed in OSM are explicitly

[27]obtained from OpenStreetMap's API: `https://overpass-turbo.eu/`, specifying objects with label "solar" in the "plant" category and within France geographic boundaries.

associated with the specific buildings on which they are installed (e.g. factory, warehouse, stores). After being assigned to either rooftop or ground-mounted types, the OSM dataset is matched to the public inventory of solar plants using either (i) ERC codes, a unique identifier for PV installations, or (ii) projects' installed capacity and location.

This allow me to identify an additional 400 units to ground-mounted types.