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The (Non) impact of the Spanish "Tax on the Sun" on photovoltaics *prosumers* uptake

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ABSTRACT

There is increasing scientific evidence of anthropic climate change. The need to shift to more sustainable energy systems is therefore compelling. Individuals are becoming key actors in the energy transition, as producers and sellers of the renewable energy they produce on-site. However, the practice of self-consumption requires to be underpinned by adequate policy mechanisms. Under this perspective, the Spanish Royal Decree (RD) 900/2015, also so-called "Tax on the Sun", aiming at regulating energy self-consumption and enhancing the engagement of Spanish citizens in the energy transition as *prosumers*, by the installation of photovoltaics, represents a challenging case study. There is anecdotal evidence that instead of supporting the diffusion of electricity self-consumption, the "Tax on the Sun" has had the opposite effect. Thus, this work aims at testing this proposition by using the synthetic control methodology (SCM), which permits to evaluate the effect of a treatment in absence of a suitable control group, as in this case. This study finds that indeed at the regional level the "Tax on the Sun" has had a negative impact, if any at all. The current barriers to *prosumerism*, and more broadly to the active involvement of citizens in the energy transition, are still many and policy-makers should address these shortcomings if they want to fully employ the potential that *prosumerism* has to offer to a just energy transition.

1. Introduction

In light of the increasing scientific evidence on a human-induced changing climate and increased visibility of its impacts, the need to shift to more sustainable energy systems has become more compelling to policy-makers. One of the features of such an energy transition is a more decentralized configuration of energy production and infrastructure (Sovacool, 2014). As energy production becomes diffused and not centralized anymore, individuals shift from being passive consumers to being active participants of the energy system (Wittmayer et al., 2021). In some cases they even become *prosumers*, as they self-produce and/or self-consume energy (Brown et al., 2020). Wittmayer et al. (2021) state that within 2050, the electricity generated by *prosumers* could cover over 50% of the demand. Given this potential, EU policy-makers have fostered the diffusion of *prosumerism*, or *self-consumption*, in the EU countries through national legislation (Inês et al., 2020).

Those national policies that have been designed for fostering the emergence of new energy governance approaches, i.e.*prosumerism*, have been proved to be pivotal in supporting electricity *self-consumption* (Varo-Martínez et al., 2021), even if in some cases have failed finally hindering the process of energy transition and decarbonization of national energy systems (Bauwens et al., 2016; Kooij et al., 2018; Wierling et al., 2018).

Under this perspective, an interesting case study of the challenging emergence of new forms of energy governance is represented by the Spanish Royal Decree (RD) 900/2015 (del Estado, 2015; Hedo, 2015), also called "Tax on the Sun". It aimed at regulating, for the first time in Spain, photovoltaic (PV) energy self-consumption by identifying the administrative, technical, and economic conditions of electricity self-consumption for residential, commercial, and industrial *prosumers*. However, concerning the "Tax on the Sun", there is anecdotal evidence that instead of supporting the diffusion of electricity self-consumption, it has had the opposite effect. In support of this narrative, the RD 900/2015 has recently been described as one of the most restrictive regulations of PV self-consumption in the world (López Prol and Steininger, 2020).

Thus, this work aims at testing the hypothesis that the "Tax on the Sun" has hindered, instead of supporting, the increase of electricity self-consumption in Spain, by using the synthetic control methodology (SCM).

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There is a broad literature investigating the process of energy transition and its implications in terms of energy governance (Tomasi and Gantioler, 2021; Sovacool, 2011; Bauwens, 2017), namely the emergence of decentralized energy systems and polycentric governance and the increasing role that non-state actors are gaining in these transformations (Frieden et al., 2021), to overcome the limitations that centralized energy governance systems have (Bauwens et al., 2016; Sovacool, 2011; Bauwens, 2017). Institutional and policy mechanisms' effectiveness in supporting the active involvement of civil society in the energy transition have been extensively investigated (Bauwens et al., 2016; Kilinc-Ata, 2016; Hoppe and de Vries, 2018; Leonhardt et al., 2022): Hoppe et al. (2018) find that while economics instruments seem to be the most widely used and effective in general (e.g. feed-in tariffs and other incentives), regulatory ones even if popular show mixed success evidence, and Matschoss et al. (2021) add that conflicting levels (i.e. local, regional, national, federal) of policy making may hinder the emergence of social innovation in the energy transition. Nonetheless, up to now to the extent of our knowledge, only Kilinc-Ata (2016) has carried out a quantitative analysis of the performance of EU countries and US states' national energy policy instruments, but using data up to 2008 and evaluating different types of policy instruments.

Moreover, based on a literature review carried out on three main scientific literature databases (Andrés, 2009), the synthetic control methodology has been very seldom used to evaluate the impacts of an energy policy (Lin and Chen, 2018; Maguire and Munasib, 2016; Upton and Snyder, 2017; Chi et al., 2021) while it has been widely applied in the discussion of effects of immigration policies, minimum wage, and taxes (Abadie, 2019). Among the very few application of the SCM in the field of the energy transition, Chi et al. (2021) implemented the SCM to assess the impact of a Chinese policy aiming to foster the roll-out of electric vehicles, Lin and Chen (2018) used the SCM to evaluate the effect of electricity tariffs to regulate residential electricity demand in China, finally both Maguire and Munasib (2016) and Upton and Snyder (2017) employed the SCM to assess the effectiveness of renewable energy policies to increase renewable generation capacity in the USA. No studies have been conducted to test the effects of the RD 900/2015 on the Spanish energy transition, and finally very few quantitative studies have offered evidence of the role of new energy governance initiatives to the energy transition (Wierling et al., 2018).

Hence, this work aims at contributing to the scientific discussion about policy mechanisms to foster new energy transition governance models by estimating the effects of a time-limited energy policy on RES expansion, i.e. the effect of the Spanish RD 900/2015 on the PV up-take in Spain are investigated for the first time. To do this, the empirical section of this work aims to test the proposition that the "Tax on the Sun" has had the opposite effect than the one expected by asking if the introduction of the "Tax on the Sun" in Spain has been effective in promoting the uptake of *prosumers*, i.e. fostering the deployment of PV systems in Spain. Based on yearly regional energy production from PV data, this paper uses SCMs to create a counterfactual version of each Spanish region from a donor pool of French, Italian, and Portuguese regions to quantify the impact of the "Tax on the Sun" in the Spanish regions after the entering into force of the RD 900/2015, compared to their counterfactual versions where no treatment has taken place. Specifically, the counterfactual for each Spanish region is created to best match energy production from PV prior to the implementation of the "Tax on the Sun" along with a series of physical (e.g. climate zone, components of PV potential and others) and socio-economic variables (e.g. income, dwelling typology and others) that affect PV systems installation. The robustness of the results is tested by performing placebo tests for each Spanish region, i.e. reassigning the treated status to each region used as control, one at the time and generating their synthetic versions. It is the first time that the SCM is used to evaluate the implementation effect of this specific policy, and this work and the specific methodology used for the analysis can be used as methodological reference for other countries and regions to evaluate the effect of their analogous national or regional policies. Furthermore, the policy implications outlined as result of the analysis conducted for the Spanish case study can be generalized to the other countries within and beyond the EU.

This paper develops as follows: section 2 provides a policy overview concerning the regulation of self-consumption in the European Union in general, and in Spain in the specific. Section 3 presents the synthetic control methodology and the data retrieved for the analysis of the effect of the "Tax on the Sun". Finally, section 4 provides the results of the analysis, and section 5 discusses the conclusions.

2. Background

2.1. Regulation of renewable self-consumption in the European Union

The Energy Union puts the citizens at its core, by supporting their active role in the energy systems, as individual or collective producers and sellers of the energy they produce on-site (Horstink et al., 2020).

The concept of self-consumption and its practice have been addressed by the Directive 2018/2001 of the European Parliament and the Council on the promotion of the use of energy from renewable sources (Parliament and Council, 2018a) (RED II), and the recast Electricity Market Directive (Parliament and Council, 2019). In both directives, consumers are entitled to consume, store and sell the electricity they have produced on site. Both directives are part of the Clean Energy for all Europeans package, shortened to Clean Energy Package (CEP). Part of the CEP is also the Regulation on the Governance of the Energy Union and Climate Action (European Parliament, 2018), which introduces the National Integrated Energy and Climate Plans (NECPs) as an instrument for the EU member states to indicate their renewable and energy efficiency objectives for the forthcoming 10-years period and the policy measures to be implemented to achieve them (Vandendriessche et al., 2017). Even if the Directive 2018/1999 includes the concepts of renewable self-consumers and renewable energy communities as national targets to be included by member states in their NECPs (Parliament and Council, 2018b), most of the EU member states lacked providing clear targets and plans concerning self-consumption and energy communities in their NECPs (Roberts and Gauthier, 2019).

These shortcomings require to be addressed soon by the EU member states since both the concept of *prosumer* and its practice are gaining momentum (Wittmayer et al., 2021; Horstink et al., 2020; Schmela et al., 2018). *Prosumers* have been defined as energy consumers who also produce their own energy from different on-site generators (Commission et al., 2017), but this works focuses on the production for self-consumption of electricity by PV. If before the term *prosumer* has been used in the EU regulation, from 2015 only the term *self-consumer* has been used (Pieńkowski, 2021). In this work, since it refers to a time range that covers the last decade, both terms will be used, *prosumerism* and self-consumption.

A distinction between gross and net-metering should be clarified, as also relevant for this study case study. In fact, gross metering refers to the amount of electricity produced by the on-site generators, recorded by the meter and exported to the grid (unidirectional metering) at a fixed tariff, while net-metering applies to the offset of the produced and consumed electricity (bidirectional metering), and just the exceeding amount of kWh is sold to the grid and registered by the meter (Ayompe and Duffy, 2013). In both cases the metering occurs monthly, while with the more recent *smart meters* production and consumption are measured real-time (Ayompe and Duffy, 2013; Pitì et al., 2017).

2.2. Energy policies regulating renewable self-consumption in Spain

Among the EU member States, Spain began to regulate the generation of power from Renewable Energy Sources (RES) in 1997, and since then 57 different energy policies have been implemented to support the increase of renewable energy in the country (IEA). The issue of energy self-consumption has been addressed by the Spanish Royal Decree (RD) 900/2015, also so-called "Tax on the Sun", which has entered into force in 2015, and it regulates administrative, technical, and economic modalities for electricity supply and generation with self-consumption (IEA).

Before the RD 900/2015 entered into force, it was not possible in Spain to self-consume the energy produced, but only to sell it to the national grid. Hence, the RD 900/2015 was welcomed as it made it possible for *prosumers* to consume their own generated electricity without buying it from the grid, i.e. switching to a net metering arrangement.

Unfortunately, the RD 900/2015 instead of supporting the diffusion of self-consumption, seems to have hindered it, by introducing some mandatory administrative procedures for the PV installation and financial barriers for the consumption of self-produced energy (Ríos et al., 2017), i.e. residential *prosumers* were not rewarded with any remuneration for any electricity exported to the grid (the surplus of electricity not self-consumed) and commercial and industrial *prosumers* were additionally charged for the self-consumed electricity (López Prol and Steininger, 2020).

After several critics, the RD 900/2015 has been repealed at the end of 2018 with the Royal Decree-Law (RDL) 15/2018 ("of urgent measures for energy transition and consumer protection", its English translation) (Hedo, 2018), which introduces changes concerning the tariffs on energy self-consumption (Varo-Martínez et al., 2021; Gallego-Castillo et al., 2021) and simplifies the administrative procedures for the connection to the grid of energy production technologies for self-consumption, among others (López Prol and Steininger, 2020). The RDL 15/2018 allows also the incorporation into the Spanish legal system of part of the content of the Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (Hedo, 2019). Finally, the RD 244/2019 replaces definitively the RD 900/2015 and established the administrative, technical, and economic conditions for the self-consumption of electricity (Hedo, 2019). Moreover, the changes introduced in terms of energy self-consumption regulation, address also the energy poverty issue, which has gained growing attention in the last years, not only in developing countries (Day et al., 2016; Clarke, 2018).

2.3. *Energy policies regulating renewable self-consumption in the donor pool countries: France, Italy and Portugal*

In France, self-consumption was regulated through the Law 2015–992 on Energy Transition for Green Growth (nationale et le Sénat, 2015) and the Law 2017–227 on Electricity Self- Consumption (nationale et le Sénat, 2017) that integrating the French Energy Code regulate the individual and collective self-consumption, stating that both producers and consumers of electricity have right to equal and non-discriminatory access to the grid (Inês et al., 2020). Italy to the contrary has not yet a specific regulation of self-consumption, but the Resolution of the Energy Regulatory Authority (ARERA) of 2013 (Autorità di Regolazione per Energia Reti e Ambiente, 2013) regulates also small self-consumption systems. Collective self-consumption has been then regulated through first the Decree Law 162/2019, later converted into the Law August 2020 (Parlamento Italiano, 2020). As just described in Italy the regulation of electricity self-consumption is very recent. Quite the opposite the Portuguese situation, where self-consumption has been given a legal definition back in 2014 by the Decree-Law 153/2014, regulating however only individual self-consumption as each production unit had to be associated to a single meter (Ministério do Ambiente, 2014). The collective self-consumption has been regulated in 2019, through the Decree-Law 162/2019 (doConselho de Ministros, 2019). Overall, individual electricity self-consumption has been given attention by local policy-makers before collective self-consumption, which is very recent, but in general EU countries have heterogeneous regulation of RES *prosumerism*, despite the intent of the EU Clean Energy Package (Horstink et al., 2020).

3. Methodology and data

3.1. *Synthetic control method*

For this study, the Synthetic Control Method (SCM), firstly developed by Abadie and Gardeazabal (2003), is identified as the most fitting methodology for estimating the effect of the RD 900/2015 policy implementation. In fact, on the one hand, the SCM aims at estimating the impacts of interventions implemented at the aggregate level, affecting a small number of large units (Abadie, 2019), on the other hand, the SCM is an econometric method that permits to evaluate the effect of a treatment in absence of a suitable control group. The SCM is based on the construction of a weighted combination of groups that can be used in the comparison with the treatment group.

In this paper, the SCM is used to compare Spanish regions, as treated units where the RD 900/2015 has been implemented, to synthetic Spanish regions, which, based on a weighted average of the regions of other three Western European countries, i.e. Italy, France, and Portugal, recreate Spanish regions as before the entering into force of the RD 900/2015. France, Italy, and Portugal have been identified as donor pool countries based on their geographical proximity to Spain, and similarity either in socio-economic data (see next section on Data), or physical features.

More specifically, disaggregated data at the regional level (NUTS 2) is used to create a synthetic control estimate separately for each region of Spain, using regional data of the donor pool countries (i.e. France, Italy, and Portugal). The estimation at regional level consents a more accurate prediction of the average effect of the investigated policy effect at the national level.

Thus, this approach permits to assess the impact of the "Tax on the Sun" by comparing the production of energy from PV in Spanish regions, before the entering into force of the RD 900/2015 and after its repeal in 2018, to the same variables in the same period in the synthetic-Spanish region (control group). Nonetheless, an important assumption must be made, namely that the "Tax on the Sun" has no effect on the other European member states that constitute the donor pool, meaning that the energy policy under study has no spillover effects on the control states (Lin and Chen, 2018).

Let J be the number of donor regions (the 13 French regions, 21 Italian regions, 7 Portuguese regions, 41 donor regions in total), $\mathbf{W} = (w_1, \dots, w_J)'$ is a $(J \times 1)$ vector of non-negative weights which sum to one, where $w_j (j = 1, \dots, J)$ represents the weight of region j in the synthetic Spanish region. The weights are chosen so that the synthetic control region is most similar as possible to the treated Spanish region before the entering into force of the "Tax on the Sun". Moreover, let $\boldsymbol{X_1}$ be $(K \times 1)$ vector of pre-treatment values of K predictors for each Spanish region (i.e. the predictors listed in Table 3), and let $\boldsymbol{X_0}$ be $(K \times J)$ matrix containing all the predictors values for all possible control region J. The SCM permits to choose $\boldsymbol{W}^*$, the vector of weights that minimizes $(X_1 - X_0 W)' V (X_1 - X_0 W)$ subject to $w_j \geq 0 (j = 1, 2, \dots, J)$ and $w_1 + \cdots + w_J = 1$, where $\boldsymbol{V}$ is a diagonal matrix with non-negative components and which diagonal values represent the relative importance of each predictor.

The optimal $\boldsymbol{W}^*$ and $\boldsymbol{V}^*$ are chosen by a nested optimization algorithm that minimizes the mean-square prediction error (MSPE) in the pre-treatment period. In this study, the R package "synth" [1] is used and the default option that uses Nelder-Mead and BFGS algorithms and returns the result for the best performing method (lowest MSPE). When optimal W^*, the one that minimizes the difference in outcomes in the pre-treatment period, has been chosen, the effect of the entering into force of the "Tax on the Sun" is assessed by analysing the differences in the energy production from PV figures after 2015 between each Spanish

[1] https://cran.r−project.org/web/packages/Synth/Synth.pdf.

region and its synthetic counterpart. Formally,

$$m_t = Y^I_{it} - Y^N_{it},$$

where m is the policy effect for each Spanish region (region i) at time t computes as the difference in the outcome for each Spanish region, Y^I_{it}, and the outcome generated for each synthetic-counterpart,

$$Y^N_{it} = \sum_{\substack{j=1 \\ j\neq i}}^{J} w_j Y^N_{jt},$$

which combines the observed outcomes for the donor pool regions (j) using the W^* resulted from the SCM.

As further described in section 3.3 2 models are developed, each one is further specified into two different sub-models, and judged the matching quality on the MSPE estimated for the outcome variable in the pre-treatment period.

Finally, to test the robustness of the impact of the treatment found by the SCM, i.e. that the analysis has been able to correctly reproduce the energy production from PV in each Spanish region in absence of the "Tax on the Sun", placebo tests are performed for each Spanish region. To do that, the treatment status is reassigned to each region listed as control (i.e. each French, Italian and Portuguese region used to create the donor pool for Spanish regions), one at a time, and generate their synthetic versions .[2] If the placebo test shows that the gap in PV production estimated for Spanish regions is unusually small relative to the gaps for the regions that did not implement the treatment, then our interpretation could be that our analysis provides significant evidence of a null or negative effect of the "Tax on the Sun".

3.2. Data

This paper uses annual region-level panel data for the period 2012–2018. The "Tax on the Sun" was adopted in November 2015, which means the novel dataset gathered for this study offers a pre-intervention period of 4 years, considering the time range 2012–2015 and considering that the impacts of the "Tax on the Sun" adoption should not have occurred before 2016. The sample period ends in 2018 since final data for 2019 are still not available for all donor pool units (i.e. French regions). Our donor pool gathers 41 NUTS2 regions, from 3 EU countries: France, Italy, and Portugal.

Table 1 shows the data for the production of solar photovoltaic energy in the four countries selected for this work. The energy production from PV accounts as the outcome variable of this study. The data used in this work has been retrieved either from the national energy utilities or statistics offices websites of the selected countries, as showed in Table 1, and covers the regional level at least for eight years. Regional data consent to control for regional attributes, which could be pivotal in countries that show very heterogeneous features like the ones selected for this work.

Such regional heterogeneity is displayed in Fig. 1, average regional energy production from PV in the years from 2011 to 2019, and Fig. 2, variation of PV production for each Spanish region over the same time range. From both figures it emerges that among the Spanish regions some can be depicted as big PV producers (i.e. Andalucía, Castilla-la Mancha, Extremadura), others as medium PV producers (i.e. Castilla y León, Comunidad Valenciana, and Región de Murcia) and finally all other regions as small PV producers, as their yearly production from PV has never exceeded 500 GWh in the time range considered in this work. Based on these descriptive statistics figures, Ceuta, Galicia, Asturias, and Cantabria have been excluded for further analysis.

Comparing the Spanish national trend of PV production with those of the three selected donor countries, it emerges that in absolute values (Fig. 3, left) until 2015 Spain was the second major producer of energy but was overtaken by France, which from the beginning of the decade shows a constant yearly growth of its production, compared to a rather flat Spanish trend. In per capita values (Fig. 3, right) even if the Spanish trend is flatter than the French one, Spain maintains the position of second major producer among the four countries. Italy is the one that shows a steeper yearly growth at the beginning of the decade, which slows down before 2014 and remains rather constant from then on both in absolute and per capita values. Both Italy and Spain show a decrease in 2016, followed by a peak in 2017, even if less noticeable for Spain. The Italian primacy is not weakened if the PV production figures are normalized by population as showed, nor size.

The latter is confirmed by the descriptive statistics of the regional energy production from PV in the four selected countries (Table 2). On the one hand, Italy is the country with the regions that on average produce the most from PV, and also the one country with the major regional producer. However, it is also the country with the most regional variation. On the other, Portugal is the country with the lowest average regional production, despite the high solar radiation rates of the country (Jäger-Waldau et al., 2019), but Portuguese regions do not show great variation in their production. Spain is the one country with on the one hand the lowest mean and lowest variation in per capita regional energy production and on the other hand the highest variation in regional energy production from PV per km2.

According to the grounding idea of the SCM, to recreate a synthetic version of Spanish regions, predictors must be identified. The variables that affect the PV installation, and thus that need to be included in the analysis, have been identified based on other similar works (Lin and Chen, 2018; Best et al., 2019; Briguglio and Formosa, 2017). Such predictors include some physical variables such as climate zone and the components that constitute the PV potential, but the need to go beyond the physical aspects led to include socio-economic factors that may

Table 1
Overview of main data for production of solar photovoltaic energy in the 4 selected countries.

Country	Territorial level	Time Range	Source
Spain	NUTS2	2011–2019[a]	Red Electrica España
France	NUTS2	2009–2018	Données et études statistiques, EDF, RTE
Italy	NUTS2 & NUTS3	2010–2019	GSE
Portugal	NUTS2	2010–2019	Direção-Geral de Energia e Geologia

[a] For Baleares, Mellilla, Canarias data starts from 2008.

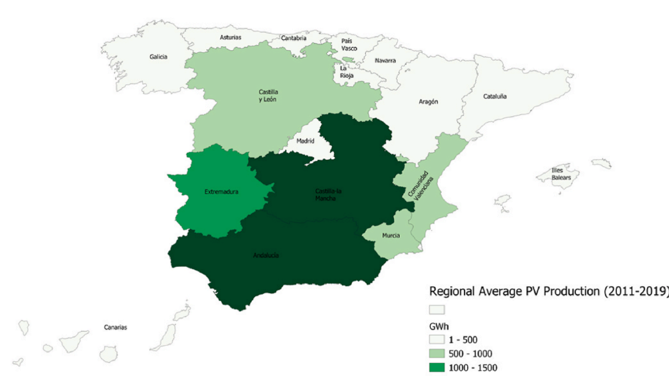

Fig. 1. Average regional energy production from PV, in the years from 2011 to 2019. Ceuta and Melilla are not displayed as their average production is nearly 0.

[2] Package "SCtools" https://cran.r−project.org/web/packages/SCtools/SCtools.pdf.

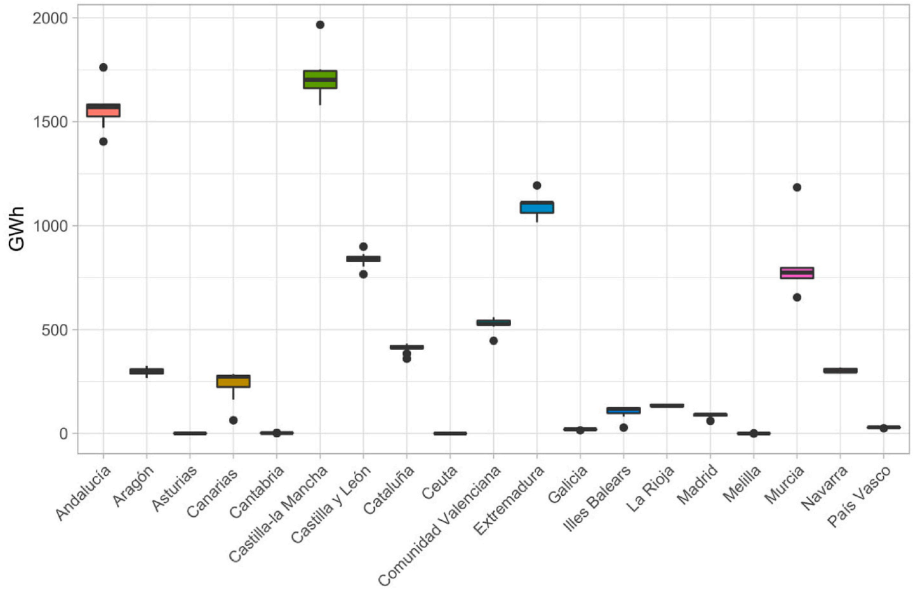

Fig. 2. Variability in regional energy production from PV in Spain, in the years from 2011 to 2019.

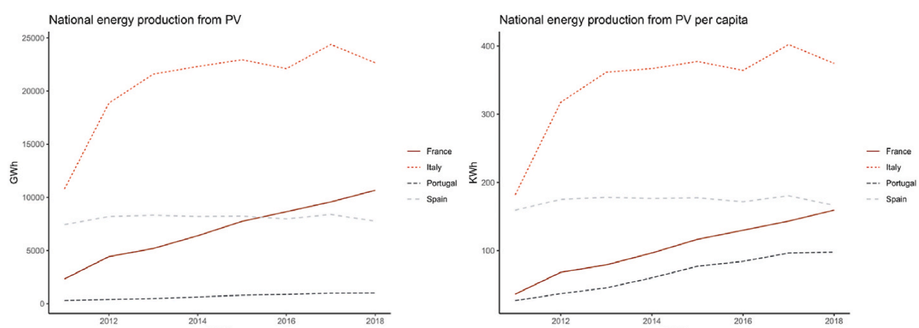

Fig. 3. Trends of national energy production from PV in the four selected countries in absolute and per capita values.

Table 2
Descriptive statistics of mean values of energy production from PV by country (NUTS2, i.e. regional data). SD in brackets.

Variable	Spain	France	Italy	Portugal
Regional energy production from PV (GWh)	406.67 (513.68)	401.283 (569.04)	910.6 (863.44)	99.01 (109.86)
Regional energy production from PV (MWh) per capita4	0.22 (0.28)	573.76 (62.07)	930.39 (342.36)	822.14 (58.04)
Regional energy production from PV per km2[5] (MWh)	16.57 (16.83)	0.10 (0.12)	0.37 (0.24)	0.11 (0.15)

Notes: 4 and 5. Population figures and data about regional surface from EUROSTAT.Régions ultrapériphériques françaises have been excluded since they are not used in the model.

Table 3
Overview of predictors data.

Variable	Territorial Level	Time Range	Source
Population	NUTS2	2008–2018	Eurostat
GDP (current market prices)	NUTS2	2008–2018	Eurostat
Household tenure	NUTS2	2010–2019	EU-SILC survey
Dwelling Type	NUTS2	2010–2019	EU-SILC survey
Education level	NUTS2	2010–2019	EU-SILC survey
Employment status	NUTS2	2010–2019	EU-SILC survey
Total disposable household income	NUTS2	2010–2019	EU-SILC survey
Climate Zone	NUTS2	present day	(Beck et al., 2018)
PV potential	NUTS2	1994–2018	Global Solar Atlas
Electricity prices for household consumers	NUTS0	2008–2019	Eurostat

affect the decision of installing PV panels, as electricity tariff structures for end-users (La Monaca and Ryan, 2017), income, renters and long-term property tenure (Briguglio and Formosa, 2017). Among the prediction variables, climate zone is assumed to be a non-time-varying predictor, electricity prices for household consumers are non-space-varying predictors (in fact they are at the national level), while the others are both time and space-varying, as Table 3 shows.

Household tenure, dwelling type, educational level, and employment status are aggregated variables coming from Eurostat data, Statistics on Income and Living Conditions,[3] covering from 2011 to 2019.

As Dube and Zipperer (2015) observe, the quality of the matching between the treated unit and its synthetic counterpart in the pre-treatment period depends on the choice of predictors. This is particularly difficult for multiple case studies, like the one in this work. In the next section (The models and quality match) the choice of different sets of predictors is discussed, which resulted in different synthetic controls.

Comparing Spanish regions to those that compose the donor pool, Table 4 shows that average regional population density and its variations are both higher in Spain than in the donor pool countries. Concerning the regional GDP, Spanish regions are richer on average only than the Portuguese ones. Such a trend in regional wealth is confirmed also looking to the regional average household disposable income: Spanish households are on average wealthier only than Portuguese ones, but most similar to the Italians (see Table 4).

Table 5 synthesizes the descriptive statistics of the multi-level predictors. Regarding the employment status, average regional rates of employed individuals are very similar in Spain and Italy (over one third of the regional population). Spain shows the highest regional unemployment rates, as well as the average share of inactive persons, with a combined average regional figure of almost 50% of individuals in working age that do not work (and probably do not perceive a full salary). Spanish regions show the highest mean educational level rate. Overall, the Spanish population is distributed equally among the four educational levels: primary (21%), lower secondary (28,5%), upper secondary (22%), and tertiary (25%). Among the donor pool countries, Portuguese population educational rates are skewed towards lower educational levels, while French and Italian populations are concentrated in the secondary education levels.

House typology and tenure type have been proved to affect the decision to adopt low carbon transition technology, e.g. PV (Sovacool et al., 2019). Concerning dwelling type, Spanish regions show a high average rate of flats in apartment buildings (buildings with 10 or more dwellings), the highest among the four countries under study, and they also show the lowest average rate of single houses. The most similar situation to Spanish regions is the Italian one. The tenure situation is more homogeneous among the four countries: the average rate of ownership is the highest among the different tenure typologies in all four countries. Spain shows the highest regional ownership rates (over 80%).

Electricity prices for household consumers are divided into three price ranges, based on annual consumption in kWh. Spanish regions are those that show the highest average prices for electricity for small and medium annual consumption, while Italian regions show a slightly higher average price for big annual consumption. Both for small and medium annual consumption Portuguese regions are those that show most similar average prices to those of Spanish regions.

Table 4
Descriptive statistics socio-economic variables, mean values, by country (NUTS2, i.e. regional data). SD in brackets.

Variable	Spain	France	Italy	Portugal
Population density	691.16	169.6	177.02	247.55
(inhabitant/km2)	(1582.55)	(242.90)	(109.41)	(297.04)
GDP	57140	160630	78685	25800
(million euros)	(61498.6)	(152335.3)	(82100.96)	(23773.7)
Household disposable income	35555	47842	39485	21116
(euros - average)	(5456.84)	(4445.24)	(5955.07)	(997.01)

[3] https://ec.europa.eu/eurostat/web/microdata/european−union−statistics−on−income−and−living−conditions.

Table 6 synthesizes the descriptive statistics of the physical predictors. Comparing the climate zone ranges in the four countries under study, Italy is the one with the coldest regions and Spain the one with the hottest. The average regional climate zones are similar in Spain and Portugal (temperate with hot/warm summer). The average size of regions is higher in France and Spain, and this latter shows the higher variation in regional size. Concerning irradiation, and the four variables characterizing it, Spanish regions are those that show the highest average figures, second only to Portuguese regions. Average regional air temperature 2 m above ground level shows its lowest figures in Italy and its highest in Spain. Spanish regional averages are closed to Portuguese ones. Finally, Spanish regions have both the highest average minimum and maximum elevation among the four countries. In their average maximum altitude are similar to Italian regions.

3.3. *The models and quality match*

Four different predictors sets are developed, as showed in Table 8, which vary according to the outcome variable (in model 1 outcome variable is yearly PV production, in model 2 outcome variable is yearly PV production per km2), and to two model specifications: the first one includes mainly socio-economic predictors and a single physical predictor (climate zone), the second one in addition to those includes specific physical predictors (variables of PV potential). As anticipated in the methodological section, for each Spanish region each model has been tested to identify the best predictor set and finally the most fitting one has been selected, based in a first stage on inspection to determine whether model fitted best, and then on the resulting minimized MSPE to choose between the two model specifications. A discussion of these results is found in the next section.

Table 7 shows the matching quality of models and their specification for each region. As already mentioned, in a first stage a choice between models has been carried out for each region based on inspection since the outcome variables are different in measurement units (yearly PV production in model 1, yearly PV production per km2 in model 2) and thus the MSPE not comparable. Then, within each model, comparison between MSPE of each specification has been realized to identify the most fitting one for each region. In general, model 2 is the one that fits more regions, and specification 2 in particular. Big, medium, and small producers, as categorized before, are evenly distributed among models and specifications.

4. Results

The synthetic regions have been constructed by combining different regions of the control group, as explained in section 3. Table 9 shows the weights, i.e. the contribution of each control region to each synthetic region. Those regions that have no contribution in any of the synthetic regions are not displayed in the table, even if they have been used in each SCM. In general, just two French regions out of 13, 13 out of 21 Italian regions have contributed in creating the synthetic Spanish regions, and just one out of 7 Portuguese regions has not contributed at all. The Portuguese regions of Alentejo and Madeira are those that have most contributed in constructing the synthetic Spanish regions, i.e. they both have contributed in 6 out 15 cases, while the French region of Île de France and the Italian Umbria have contributed in one third of the cases. Synthetic Madrid is the only treated region that is entirely explained by just one donor region (i.e. the Italian Liguria), and synthetic Comunidad Valenciana is the treated region with more donor regions contributions (i.e. 8). In average each synthetic region received the contribution of 4 donor pool units.

As mentioned before, the selection of predictors is pivotal in SCM analysis. Predictor weights have been reviewed in Table 10 to determine the selected predictor variables' strength in explaining the outcome. In average, the electricity price tariffs for small consumption (i.e. annual consumption <1000 kWh) is the predictor with more explanation

Table 5
Descriptive statistics of socio-economic variables with more than one level, mean values by country (NUTS2, i.e. regional data). SD in brackets.

Variable	Level	Spain	France	Italy	Portugal
Employment status (%)	At work	37.14 (5.447055)	47.546 (15.6422)	38.17 (5.329505)	40.25 (2.563542)
	Unemployed	11.464 (4.975524)	5.85456 (2.44894)	7.241 (3.267011)	8.806 (2.277895)
	In retirement orearly retirement	13.687 (3.923555)	16.616 (6.79132)	17.89 (3.210029)	21.05 (1.676626)
	Other inactive person	37.71 (4.480731)	29.98 (12.31933)	36.69 (5.26113)	29.89 (1.120186)
Dwelling type (%)	Detached house	16.791 (12.1521)	56.33 (16.59221)	27.53 (4.435498)	43.69 (5.959901)
	Semi-detached or terraced house	22.771 (14.84185)	23.23 (10.33566)	24.95 (5.187187)	22.17 (7.059087)
	Apartment or flat in a buildingwith less than 10 dwellings	19.100 (5.687192)	6.863 (5.552401)	24.46 (4.053179)	19.835 (3.67747)
	Apartment or flat in a building with 10 or more dwellings	41.34 (14.49875)	13.573 (15.77855)	23.06 (5.869813)	14.2991 (6.341115)
Tenure status (%)	Owner	82.34 (6.502463)	70.87 (5.596504)	77.75 (2.40163)	77.71 (1.487297)
	Tenant or subtenant paying rent atprevailing or market rate	9.304 (4.411984)	14.388 (3.637693)	11.826 (2.211145)	9.985 (1.248573)
	Accommodation is rented at a reduced rate (lower price than market price)	2.86312 (3.40098)	12.627 (4.658038)	3.496 (1.201697)	5.331 (1.054452)
	Accommodation is provided free	5.497 (3.305515)	2.116 (0.971788)	6.930 (1.472589)	6.970 (0.8507982)
Educational level (%)	Pre-primary education	3.230 (4.553966)	2.165 (1.679729)	2.367 (1.029561)	3.484 (3.925971)
	Primary education	20.968 (7.393534)	16.2557 (8.089488)	13.596 (2.388003)	43.96 (7.130134)
	Lower secondary education	28.50 (5.660657)	21.0130 (8.769922)	29.61 (3.080933)	21.45 (0.6598444)
	Upper secondary education	21.93 (2.835756)	38.80 (10.07222)	38.66 (3.008103)	17.91 (1.834282)
	Post-secondary non tertiary education	0.31844 (0.334464)	0.1197 (0.2016436)	2.3600 (1.074519)	0.5850 (0.1880489)
	Tertiary education	24.773 (6.465168)	21.648 (7.724703)	13.411 (2.472514)	12.611 (2.236721)
Electricity prices for household consumers	Consumption <1000 kWh (euros)	0.4489 (0.1031493)	0.2814 (0.0490744)	0.3080 (0.06491449)	0.3676 (0.026542)
	Consumption between 1000 kWh and 2500 kWh (euros)	0.2485 (0.03982711)	0.1758 (0.02400938)	0.1987 (0.02604351)	0.2220 (0.02962592)
	Consumption between 2500 kWh and 5000 kWh (euros)	0.2117 (0.02853061)	0.1542 (0.02124848)	0.2195 (0.01507185)	0.2007 (0.02970179)

strength, as it contributes in average to explain the 7.5% of the synthetic counterpart of the Spanish regions. Another predictor with high explanation strength is the electricity production from PV before 2015. Other explanatory predictor variables are the share in the region of apartments or flats in buildings with 10 or more dwellings, electricity price tariffs for medium consumption and regional GDP.

The regional SCM results are presented clustered per model to be comparable (the outcome variable is different in model 1 than model 2, see section 3.3). The pre-treatment trends in Figs. 4–5 confirm the quality of the synthetic control estimates. In some cases more than in others, e.g. Illes Balears and Canarias, the real and the synthetic version of the region have nearly identical PV production trends in the pre-treatment period, and overall the general trends are similar, suggesting the good match of the synthetic counterparts.

Interestingly, in general, with small variations among the regions, the effect of the “Tax on the Sun” on the PV production appears to be nearly zero, if not even negative. The analysis in fact gives empirical evidence that the “Tax on the Sun” did not lead to more PV electricity production in the Spanish regions, and suggestive evidence that it might have even led to decrease the electricity production from PV, compared to the production that might have been if the “Tax on the Sun” had never entered into force. These results suggest that, if the “Tax on the Sun” has not fostered the diffusion of PV panels, it seems to have even slightly hindered it, e.g. by introducing some mandatory administrative procedures for the PV installation and financial barriers for the consumption of self-produced electricity.

To confirm this, and evaluate the robustness of the results, placebo tests are performed for each Spanish region. Hence, the treatment status is assigned to each of the donor pool regions and iteratively applied the SCM used to assess the effect of the “Tax on the Sun” to every other region in the donor pool, similar to Abadie and Gardeazabal (2003); Abadie et al. (2010); Bertrand et al. (2004). The same model specification applied for each individual Spanish region has been used also to run the placebo tests with the donor pool regions. Figs. 6–7 show the results for the placebo test for each Spanish region. Here too, the results of the placebo tests are presented clustered per model to be comparable. The lighter lines represent the difference in energy production from PV (either in absolute values or per squared km, depending on the model) between each region in the donor pool and its synthetic version. The solid black lines represent the same gap estimated for the Spanish region in question. As Figs. 6–7 display, the estimated gap in PV production for the Spanish regions after 2015 is nearly zero in many cases, and very small compared to the overall distribution of the gaps of the placebos. In none of the regions, the gap is positive after 2015, meaning that the “Tax on the Sun” has had a negative effect if any at all.

5. Conclusions and policy implications

The Energy Union envisages an active role for citizens and requires the European member states to regulate and promote energy *prosumerism*. This study addresses the effects of a national energy policy in boosting the production of energy from renewable energy sources for

Table 6
Descriptive statistics physical variables, mean values by country (NUTS2, i.e. regional data). SD in brackets.

Variable	Spain	France	Italy	Portugal
Climate Zone[a]	9.26 (3.23)	14.38 (2.06)	14.05 (6.23)	8.571 (1.40)
Area (km2)	26630 (29486.11)	41843 (22345.36)	14370 (7505.88)	13173 (12450.63)
Direct Normal Irradiation (average - kWh/m2)	34.89 (17.48)	15.69 (10.96)	26.29 (10.32)	36.57 (19.20)
Global Horizontal Irradiation (average - kWh/m2)	35.16 (17.91)	13.62 (10.05)	27.52 (13.63)	42.71 (11.96)
Diffuse Horizontal Irradiation (average - kWh/m2)	17.37 (10.81)	18.77 (7.73)	20.9 (11.33)	24.14 (12.26)
Global Titled Irradiation (average - kWh/m2)	34.79 (17.51)	14.62 (9.67)	2.95 (12.81)	38.43 (14.39)
Air Temperature (minimum - °C)[b]	7.27 (3.30)	6.24 (5.35)	2.83 (6.10)	11.51 (2.93)
Air Temperature (maximum - °C)[b]	16.93 (1.85)	13.78 (2.01)	16.21 (1.87)	17.54 (1.07)
Terrain Elevation (minimum - m)	121.9 (160.78)	24.92 (35.68)	42.81 (98.52)	5.14 (7.63)
Terrain Elevation (maximum - m)	1771 (450.83)	1209 (1030.52)	1729.318 (854.00)	1081 (477.82)

[a] " Legend linking the numeric values in the maps to the Köppen-Geiger classes (Beck et al., 2018): 1–3: Tropical; 4–7: Arid; 8–16: Temperate; 17–28: Cold; 29–30: Polar."
[b] "Air Temperature at 2 m above ground level".

Table 7
MSPE per model specification.

Region	Model 1.1	Model 1.2	Model 2.1	Model 2.2
Andalucía	6912.077	**674.3799**		
Aragón	**224.1527**	235.4118		
Canarias			22.00586	**0.2564035**
Castilla - La Mancha	**4547.136**	22626.91		
Castilla y León	4446.676	**1360.052**		
Cataluña	**732.5284**	2018.189		
Comunidad Valenciana			3.677112	**1.273699**
Extremadura			**0.8844681**	6.41344
Illes Balears			0.3307446	**0.06337444**
La Rioja			4.920092	**2.865504**
Madrid	**40.87786**	164.0068		
Melilla			**1.98**	–[a]
Murcia			**6.058749**	6.109357
Navarra			5.107201	**2.927993**
País Vasco	**15.0212**	141.7399		
Excluded: Galicia, Asturias, Cantabria, Ceuta				

Notes: In bold the minimized MSPE, hence the one best fitting.
[a] Model 2.2 for Melilla is not possible to be run because data is missing for PV potential variables.

self-consumption. More specifically, it estimates the impact of the Spanish Royal Decree (RD) 900/2015, so-called “Tax on the Sun”, aiming at regulating energy self-consumption from PV and enhancing the engagement of citizens in the energy transition as *prosumers* in Spain. The “Tax on the Sun” entered into force in November 2015 and regulated for the first time in Spain administrative, technical, and economic modalities for electricity supply and generation with self-consumption. This paper applies the Synthetic Control Method to investigate if after the entering into force of the “Tax on the Sun” the production of energy from PV has enhanced in the Spanish regions as effect of the case study policy, comparing them to their counterfactual synthetic versions, as the regions would be if not impacted by the policy. As donor pool regions to recreate the Spanish regions as if the “Tax on the Sun” had never entered into force, French, Italian, and Portuguese regions are used, as they show similar socio-economic and physical features to the Spanish regions.

Table 8
Predictor sets by model specification.

OUTCOME VARIABLE	Predictor	Levels	MODEL 1 Yearly PV production (GWh)		MODEL 2 Yearly PV production per km2 (MWh)	
Domain			m1.1	m1.2	m2.1	m2.2
Socio-economic features	Population density	1	x	x	x	x
	GDP	1	x	pc	x	pc
	Employment	4	x	x	x	x
	Dwelling type	4	x	x	x	x
	Tenure	4	x	x	x	x
	Education	6	x	x	x	x
	Income	1	x	x	x	x
	Price	3	x	x	x	x
Physical features	Climate Zone	1	x		x	
	Area	1	x	x		
	Direct Normal Irradiation	2		av		av
	Global Horizontal Irradiation	2		av		av
	Diffuse Horizontal Irradiation	2		av		av
	Global Titled Irradiation	2		av		av
	Air Temperature	2		x		x
	Terrain Elevation	2		x		x

Notes: Outcome variable in the pre-treatment period is also used as predictor. “pc” stands for per capita, “av” for average. Levels refer to the number of categories for nominal variables, e.g. Employment that is categorized into at work, unemployed, In retirement or early retirement, Other inactive person. Continuous variables have only 1 level. The descriptive statistics tables presented in the previous section show the level for all variables.

Predictors have also been identified, which are needed for the SCM to properly work. Physical and socio-economic factors that may affect the installation of PV panels have been used as predictors in the two models developed, which mainly vary based on the outcome variable (PV production or PV production per km2).

This study finds that at the regional level in Spain the “Tax on the Sun” has had a negative impact, if any at all. In fact, the results of the analysis carried out show evidence that in every Spanish region under investigation after the entering into force of the “Tax on the Sun” there has been either a decline or no change in electricity production from PV compared to what would have been if the policy would not have been implemented in those regions. In other words, the “Tax on the Sun” has not positively impacted the production of electricity from PV in Spain, i. e. hindering, or not properly supporting, electricity self-consumption. This result's robustness is confirmed by placebo tests that have been run for each Spanish region. They consist of reassigning the treatment status to each of the donor pool regions and applying for each of them the SCM. These results confirm the hypothesis, stated in section 1, that the “Tax on the Sun” has hindered instead of supporting PV self-consumption. The inefficacy in fostering electricity self-consumption from PV of the “Tax on the Sun” means generally a slowdown of the decarbonization process for Spain, hindering the potential that *prosumers* of the residential, commercial and industrial sectors have. The pivotal role that energy policies play in underpinning energy transition processes is confirmed by the case study under investigation in this work, that showed a policy failure.

Some could be the reasons undermining the effect of the “Tax on the Sun”, other than the additional administrative burden for the PV installation and financial barriers for the consumption of self-produced electricity, which are those that had been already identified by previous studies (López Prol and Steininger, 2020; Ríos et al., 2017). The first one is the high tariffs for energy consumption, above all for small and medium consumers in Spain. In fact, Spanish regions show the highest

Table 9
The weights of each control unit for each synthetic unit.

	Andalucía	Aragón	Canarias	Castilla- la Mancha	Castilla y León	Cataluña	Comunidad Valenciana	Extremadura	Illes Balears	La Rioja	Madrid	Melilla	Murcia	Navarra	País Vasco
Île de France (FR)	0.091					0.182			0.188			0.974			0.199
Nord-Pas-de-Calais - Picardie (FR)			0.012				0.398					0.289			
Piemonte (IT)						0.123									
Valle d'Aosta /Vallée d'Aoste (IT)				0.054	0.257				0.4						
Liguria (IT)		0.512							0.145		1				
Toscana (IT)							0.222							0.001	
Umbria (IT)		0.488			0.215					0.027				0.154	0.027
Marche (IT)					0.592									0.001	0.003
Lazio (IT)														0.001	
Campania (IT)												0.025			
Puglia (IT)	0.418			0.435					0.108				0.353		
Basilicata (IT)						0.438							0.004		
Calabria (IT)	0.006												0.001		
Sicilia (IT)			0.259				0.007								
Sardegna (IT)							0.007								
Norte (PT)					0.138										
Algarve (PT)							0.001	0.013							
Centro (PT)	0.475		0.306				0.006								
Alentejo (PT)	0.01			0.552			0.172	0.003		0.071			0.353		
Açores (PT)							0.266		0.537					0.386	0.772
Madeira (PT)			0.435				0.319	0.585	0.022	0.502				0.458	

Notes: In the table only those regions that had some weight in estimating any synthetic treated unit compare. The following regions do not compare in the table since their weight was 0 in estimating all synthetic regions: Centre - Val de Loire (FR), Bourgogne - Franche-Comté (FR), Normandie (FR), Alsace - Champagne-Ardenne - Lorraine (FR), Pays-de-la-Loire (FR), Bretagne (FR), Aquitaine - Limousin - Poitou-Charentes (FR), Languedoc-Roussillon - Midi-Pyrénées (FR), Auvergne - Rhône-Alpes (FR), Provence-Alpes-Côte d'Azur (FR), Corse (FR), Lombardia (IT), Provincia Autonoma di Bolzano/Bozen (IT), Provincia Autonoma di Trento (IT), Veneto (IT), Friuli-Venezia Giulia (IT), Emilia-Romagna (IT), Abruzzo (IT), Molise (IT), Lisboa (PT).

Table 10
The contribution of each predictor to each synthetic control region.

	Andalucía	Aragón	Canarias	Castilla- la Mancha	Castilla y León	Cataluña	Comunidad Valenciana	Extremadura	Illes Balears	La Rioja	Madrid	Melilla	Murcia	Navarra	País Vasco
Population density	1%	5%	2%	1%	0%	4%	0%	0%	0%	0%	2%	19%	4%	0%	3%
Climate Zone		6%		1%		4%		13%			10%	0%	1%		3%
GDP		14%		1%		3%		14%			0%	0%	4%		4%
GDP per capita (in thousand euros)	3%		0%		3%		0%		1%	2%				0%	
Area	1%	0%		1%	9%	5%					11%				1%
Direct Normal Irradiation	4%		3%		3%		0%		0%	0%				0%	
Global Horizontal Irradiation	0%		0%		4%		0%		0%	1%				3%	
Diffuse Horizontal Irradiation	7%		5%		0%		1%		4%	0%				0%	
Global Titled Irradiation	1%		1%		4%		0%		0%	0%				0%	
Air Temperature min	3%		1%		5%		1%		2%	0%				0%	
Air Temperature max	0%		4%		5%		1%		0%	0%				0%	
Terrain Elevation min	2%		0%		1%		0%		0%	2%				1%	
Terrain Elevation max	1%		10%		4%		4%		1%	0%				1%	
Electricity prices for small household consumption	6%	1%	18%	11%	5%	4%	14%	10%	8%	5%	0%	0%	4%	16%	10%
Electricity prices for medium household consumption	3%	0%	12%	6%	2%	4%	9%	8%	2%	3%	9%	0%	3%	10%	7%
Electricity prices for big household consumption	2%	1%	1%	3%	2%	3%	0%	1%	1%	0%	0%	0%	4%	0%	2%
Employment At work	1%	1%	0%	4%	2%	4%	0%	0%	5%	0%	1%	0%	3%	0%	3%
Employment Unemployed	5%	3%	6%	2%	2%	3%	0%	1%	1%	3%	0%	0%	4%	0%	3%
Employment Retirement	7%	1%	10%	3%	0%	4%	5%	5%	9%	0%	1%	12%	4%	5%	2%
Employment Inactive	2%	1%	1%	8%	3%	4%	1%	1%	2%	0%	0%	8%	6%	3%	2%
Dwelling Detached house	6%	8%	1%	8%	6%	3%	5%	1%	2%	8%	3%	4%	5%	2%	1%
Dwelling Semi-detached	2%	0%	1%	5%	2%	4%	1%	10%	1%	7%	0%	0%	3%	5%	7%
Dwelling Building < 10 dwelling	5%	1%	1%	1%	2%	3%	0%	3%	2%	4%	2%	0%	3%	4%	2%
Dwelling Building > 10 dwelling	6%	16%	1%	4%	6%	3%	2%	0%	2%	5%	16%	11%	5%	3%	3%
Tenure Owner	0%	7%	0%	0%	3%	3%	7%	2%	0%	7%	11%	9%	2%	9%	3%
Tenure Tenant	0%	9%	0%	0%	0%	3%	6%	1%	6%	10%	1%	7%	1%	9%	8%
Tenure Reduced rent	2%	3%	0%	4%	2%	1%	3%	1%	0%	3%	6%	9%	4%	3%	1%
Tenure Free rent	2%	0%	1%	1%	0%	4%	2%	1%	2%	2%	0%	9%	2%	3%	4%
Pre-primary education	4%	2%	3%	7%	1%	4%	1%	1%	8%	1%	1%	2%	2%	1%	3%
Primary education	3%	5%	3%	6%	7%	3%	5%	0%	6%	1%	0%	2%	5%	3%	4%
Lower secondary education	0%	0%	1%	3%	2%	3%	4%	2%	1%	3%	0%	0%	2%	1%	2%
Upper secondary education	2%	1%	3%	5%	4%	4%	3%	2%	3%	7%	1%	1%	3%	7%	5%
Post-secondary education	4%	0%	7%	2%	1%	4%	7%	3%	2%	2%	1%	5%	6%	7%	6%
Tertiary education	7%	3%	2%	2%	1%	4%	4%	3%	12%	4%	0%	0%	5%	0%	7%
Household disposable income (average)	3%	6%	1%	2%	5%	4%	1%	2%	3%	0%	1%	0%	4%	1%	0%
Household disposable income (sd)	1%	4%	1%	2%	3%	4%	0%	2%	0%	1%	14%	0%	3%	2%	2%
PV production (2012–2015)	5%	0%	2%	9%	3%	4%	15%	14%	11%	19%	11%	2%	6%	2%	3%

Notes: those predictors which have no figure are not included in the model specification. For reference refer to Table 8.

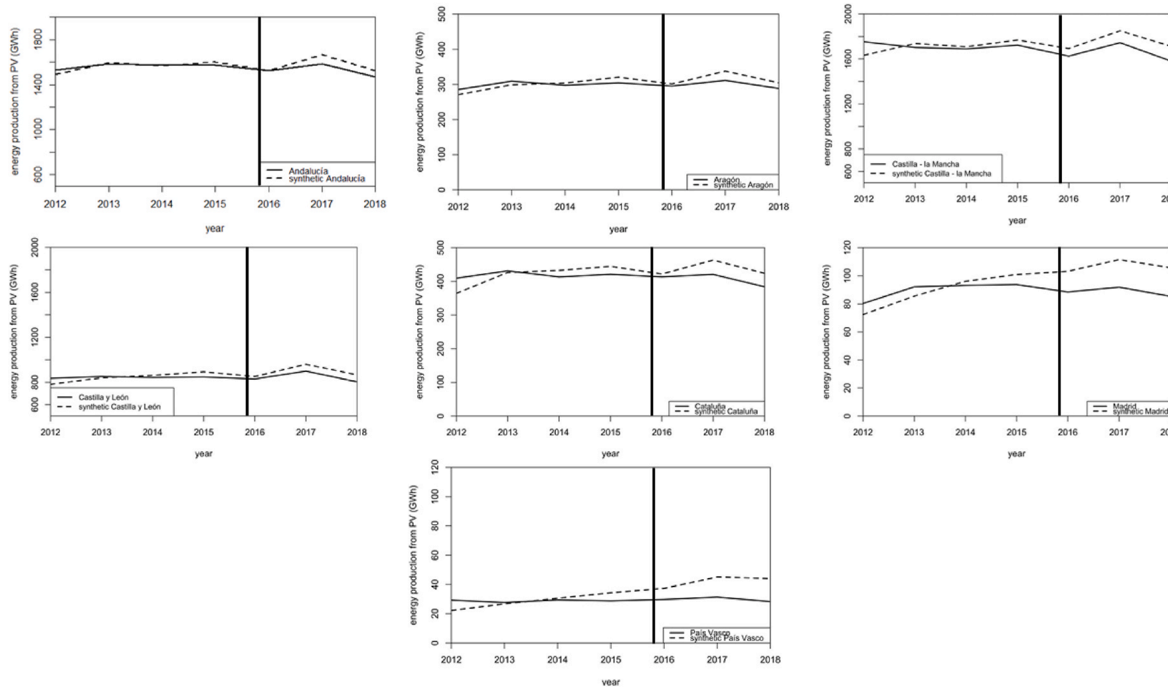

Fig. 4. Trends in energy production from PV (GWh) in region vs synthetic counterpart: regions that fitted better in model 1
Notes: The vertical dashed lines indicate late 2015, the point in time when the "Tax on the Sun" entered into force.

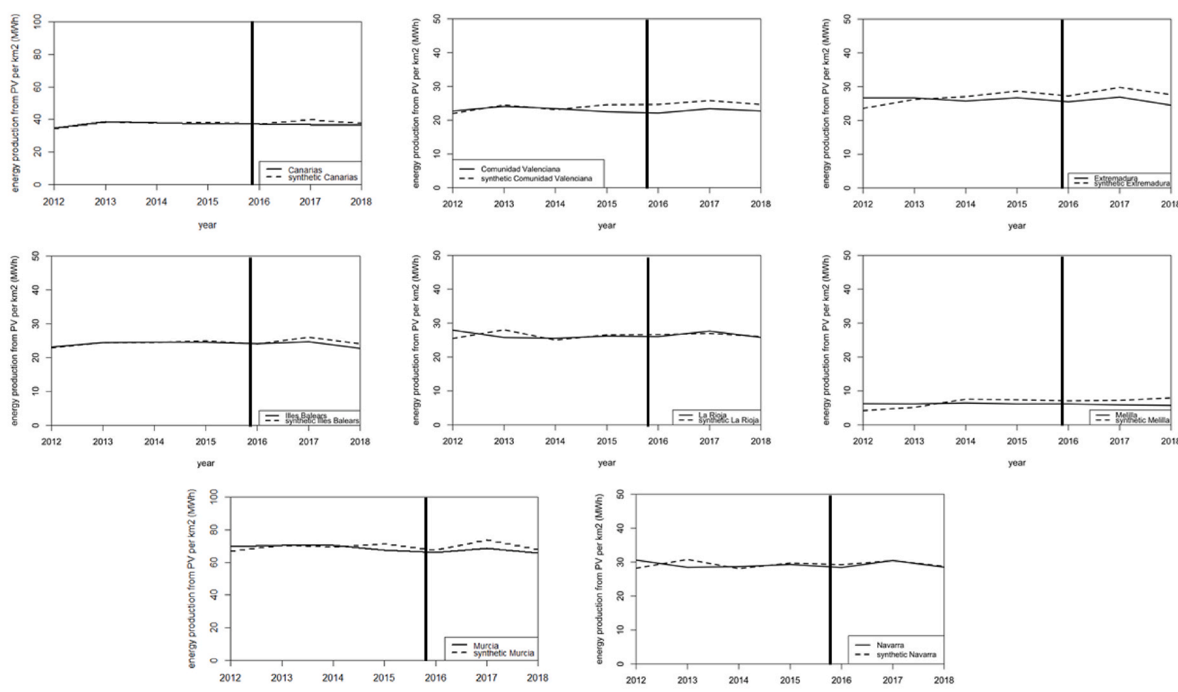

Fig. 5. Trends in energy production from PV (MWh/km2) in region vs synthetic counterpart: regions that fitted better in model 2
Notes:The vertical dashed lines indicate late 2015, the point in time when the "Tax on the Sun" entered into force.

electricity prices for household consumers, and this factor has played an important part in creating the synthetic counterparts of Spanish regions. This would also confirm that the financial barriers that the "Tax on the Sun" introduced, by not allowing a remunerative reward for any electricity exported to the grid or even by charging commercial and industrial *prosumers* for the self-consumed electricity, have had a negative effect on production for self-consumption.

Another explanation for the inefficacy of the "Tax on the Sun" could also be the prevalent dwelling type in Spain, i.e. the fact that over 40% of the Spanish population lives in big apartment buildings, and are hence co-owner of the roofs. This could partially explain the low rate of adoption of PV panels, and the ineffectiveness of the "Tax on the Sun" in fostering it. The share of apartments or flats in buildings with 10 or more dwellings on the totality of dwellings at the regional level has been as well one of the predictors that mostly contributed to create the synthetic counterparts of the Spanish regions, confirming hence the pivotal role of

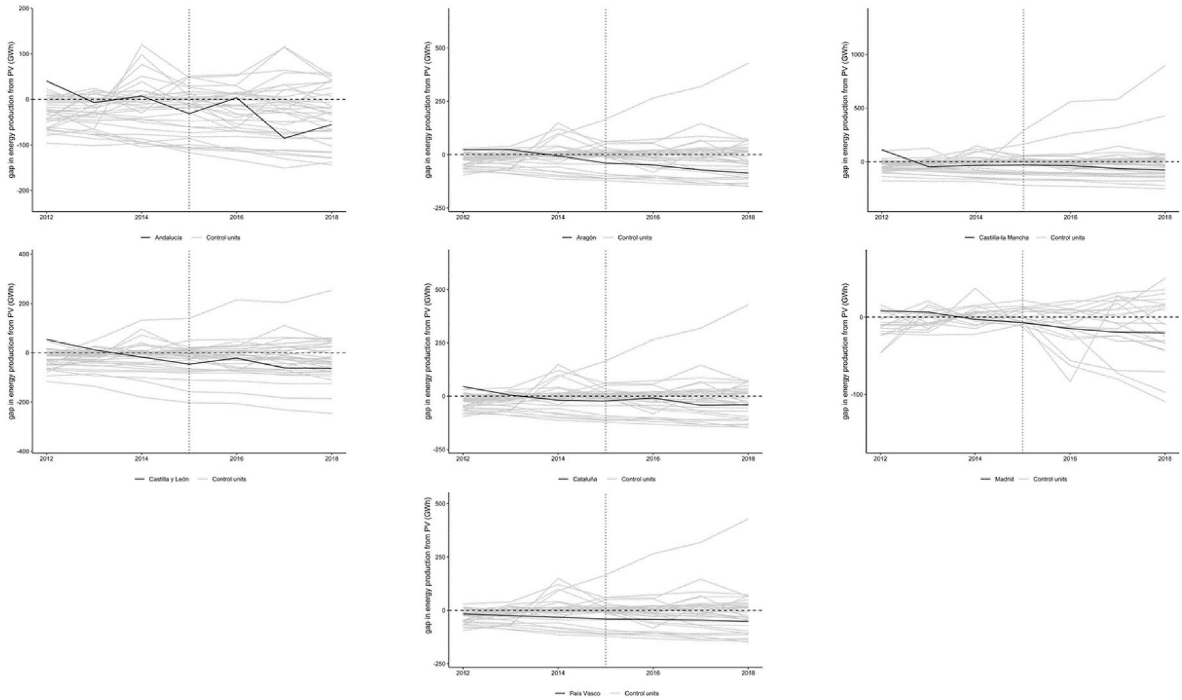

Fig. 6. Results of the difference in production from PV between each Spanish region (model 1) and its synthetic counterpart (solid line), and the results of placebo tests (lighter lines), assigning the treatment to donor pool regions
Notes: Regions with high pre-treatment MSPE are excluded from the plot.

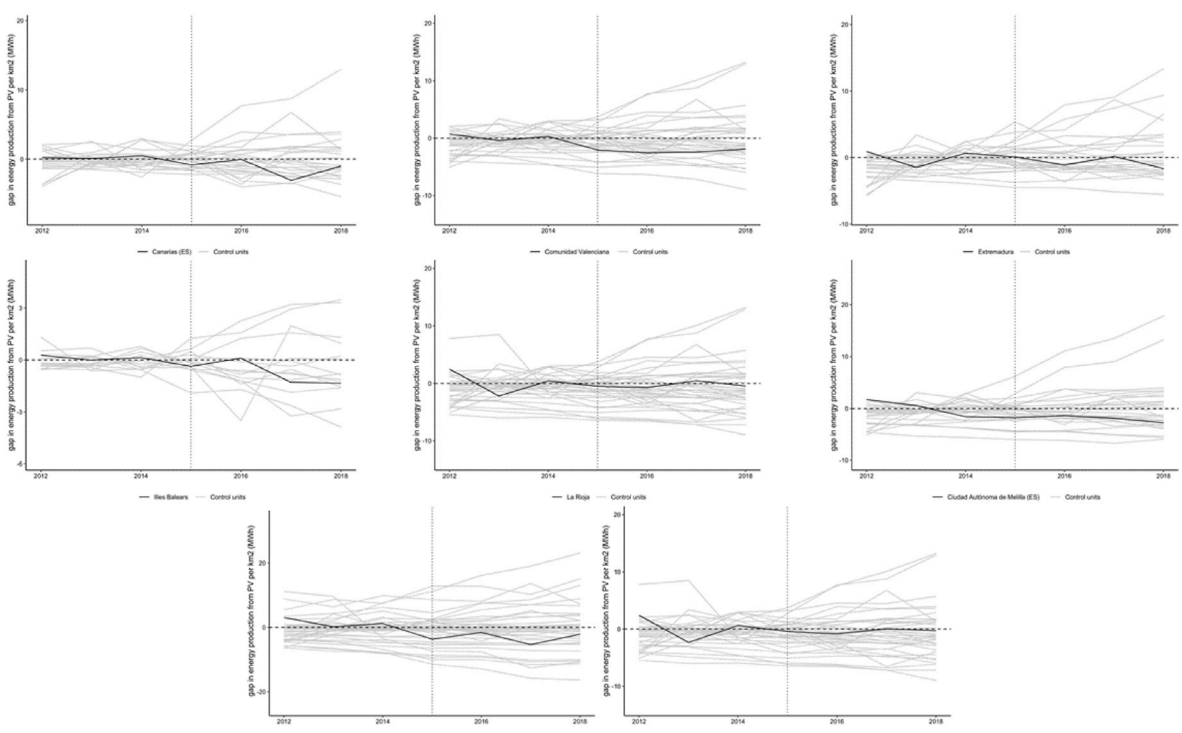

Fig. 7. Results of the difference in production from PV between each Spanish region (model 2) and its synthetic counterpart (solid line), and the results of placebo tests (lighter lines), assigning the treatment to donor pool regions
Notes: Regions with high pre-treatment MSPE are excluded from the plot.

this feature on the limited emergence of energy *prosumerism* in Spanish regions.

A limit in the design of this work is the length of the pre-treatment period: the longer it is, the more precise the predictor information for the synthetic unit (Dube and Zipperer, 2015). The time range of 4 years is short compared to other similar works. Moreover, the SCM permits to understand the effects of the "Tax on the Sun", but gives only a suggestion of the factors that may have had a role in leading to that outcome, also based on the selection of predictors to be included in the model.

The adoption of solar PV systems in households has been demonstrated to bring many benefits. However, it also raises some questions in terms of equity and affordability (Sovacool et al., 2019). The economic barriers, i.e. the financial affordability of the PV system technology, have not been confirmed by this study, but they should be the focus of future research.

Based on the results of this study, some policy implications are outlined. Policy-makers should ease administrative procedures to install PV panels on co-shared spaces, i.e. roofs, in multi - apartment buildings. This kind of dwellings are very diffused in Europe: in 2019 almost half of the dwellings in the EU 27 could be depicted as flat in a building with less or more than ten dwellings, with some variation among member states, and the highest share of 66% in Latvia .[4] National regulation should pay special attention to this kind of dwellings, where it is more difficult to install technologies for the production of energy for self-consumption (Sovacool et al., 2019; Balest et al., 2021).

For those citizens that have already installed PV panels or are planning to do so, their national or local regulators must envision a fair remuneration for the electricity exported to the grid, e.g. through feed-in-tariffs. As the Spanish case study demonstrated this is a pivotal issue, and if not considered could represent a substantial constraint.

In Spain such matters have been considered after the "Tax on the Sun" was repealed first and replaced then, by the RDL 15/2018 and the RD 244/2019 that in fact introduced a surplus compensation mechanism and simplified the technical requirements and administrative procedures and seem to better foster PV self-consumption in Spain (Varo-Martínez et al., 2021; López Prol and Steininger, 2020; Gallego-Castillo et al., 2021). Moreover, the RD 244/2019 also considers the emerging issue of energy poverty. Future research could investigate the effects of the new regulation (RD 244/2019), also in an energy justice perspective. Moreover a comparative analysis of the "Tax on the Sun" and the RD 244/2019 and their effects could further shed light on the role that the regulation requirements have on the promotion of PV self-consumption and lead to key policy implications.

Finally, national policy-makers have to make sure that by regulating energy self-consumption they do not widen the already existing gap of social inequality. As already mentioned, those who generate energy for self-consumption save money and even earn if feed-in-tariffs are in place. The prices of PV modules have been dropping since 2009 (Taylor et al., 2016), while their efficiency and overall performance have been improving, making the initial investment less burdensome for potential *prosumers*. However, an initial investment is anyhow needed and those individuals who already have lower-incomes, or find themselves in conditions of vulnerability, may find it impossible to become *prosumers*. National regulators should pay particular attention to those individuals who may be excluded from the current process of the energy transition.

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The responsibility for all conclusions drawn from the EU-SILC data lies entirely with the author.

CRediT authorship contribution statement

Silvia Tomasi: has covered all roles, from, Conceptualization, Formal analysis, Writing – review & editing.

Declaration of competing interest

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

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