The impact of policy on the efficiency of solar energy plants in Spain. A production-frontier analysis.

Abstract

The analysis of the impact of remuneration schemes for renewable electricity, and solar photovoltaics (PV) in particular, on the effectiveness of renewable energy deployment and the total costs of support has received a considerable attention in the past. In contrast, the literature on the effects of deployment support on productive efficiency and, more specifically, on the incentives to locate the plants in the sites with the best renewable energy resources is tiny. This article covers this gap in the literature. Its aim is to identify the impact of successive feed-in tariff (FIT) reforms on the location of solar PV plants in Spain between 2009 and 2013 using a unique dataset of PV plants and a panel stochastic production-frontier model. The analysis shows that more generous FITs, i.e. those providing a higher net support (support levels minus generation costs) have not encouraged the location of those plants in the best sites. Our results suggest that the design elements in instruments to support the deployment of renewable energy projects should carefully be chosen in order to encourage the selection of the best sites.

Key words: feed-in tariffs, solar PV, Spain, degression, productive efficiency.

1. Introduction

The literature on the analysis of the effects of remuneration schemes for electricity from renewable energy sources (RES-E) in general, and solar photovoltaics (PV) in particular, on the effectiveness of RES-E deployment and the total costs of support is relatively abundant. In contrast, and to the best of our knowledge, the effects of deployment support on productive efficiency and, more specifically, on the incentives to locate the plants on the sites with the best renewable energy resources, have not received a comparable degree of attention.

This article covers this gap in the literature, focusing on the impact of more generous support regulations on productive efficiency. Its aim is to identify the effect of successive feed-in tariff (FIT) reforms on the location of PV plants in Spain between 2009 and 2013 using a unique dataset of plants, which contains details on their techno-economic features, and a panel stochastic production-frontier analysis which handles heterogeneity issues.

Our starting point is that, the more generous the regulation, the lower the incentive to locate the plants in the places with the best solar resources. This is obviously a policy-relevant issue since it would be an additional reason to avoid too generous policies. A RES-E promotion scheme which leads to excessive remuneration levels has consequences not only on the total amount of support being granted (and, thus, distributional impacts due to rent transfers from producers to consumers), but may also have detrimental effects on the productive efficiency of the scheme.

From an efficiency point of view, it is relevant to locate the plants in the places with the best renewable energy resources. In contrast to fossil-fuel fired plants, production from solar and wind generation is largely driven by local climate conditions, and this greatly increases the variance in levelized electricity costs (LCOE) across different locations. Scarcity of high-quality locations will tend to make the cost of a new plant higher than the pre-existing average (Borenstein 2011, p.70). If the support scheme does not promote the location of PV plants in the best sites, then there would be an efficiency loss, since more generation (or lower costs) would be possible elsewhere for the same level of installed capacity. Having more PV capacity than needed to generate a given amount of PV electricity represents a classical problem of overcapacity. This is particularly problematic in sectors with high fixed costs, as in the capital-intensive renewable energy sectors. At the system level, overcapacity results in the underutilisation of assets which, in turn, results in a suboptimal allocation of economic resources. As stressed by Okazaki et al (2018, p.2), excess capacity is one source of social inefficiency; it might cause capital misallocation, create unnecessary running costs or limit land use.

Efficiency is defined in this article as productive efficiency. Production efficiency occurs when the maximum number of goods are produced with a given amount of inputs, e.g., at the production possibilities frontier. When factor inputs (such as solar irradiation) are underemployed, some potential output is missed. Reaching points, which are not in the production possibilities frontier, would not be productively efficient; and the further a given plant is from this frontier, the more inefficient it is. In other words, there is an opportunity cost in not using the installed capacity to the greatest extent possible.

This definition of efficiency in terms of production efficiency is in line with many contributions in the RES-E literature, including Schmalensee (2011), Fürsch et al (2010), Green and Yatchew (2012), Borenstein (2011), Joskow (2011), Heal (2010) and Aune et al (2012). It refers to the achievement of an optimal allocation of resources by encouraging technologies, locations and sizes which minimise generation costs (Huber et al 2004). This involves asking whether a given amount of RES generation can be achieved at the lowest possible costs. In the case of a given renewable energy technology, such as solar PV, this mainly requires production at the best sites (Schmalensee 2011, p.9). Since the same MW of installed capacity can lead to different levels of electricity generation (and/or different costs), depending on its location, it is more efficient to have the MWs installed where they generate more electricity (i.e., more MWh of generation per unit of MW of installed capacity).

The inefficient location of renewable energy plants might be related to the choice of support schemes, i.e. to the promotion instrument and/or, as shown in this article, its design elements. Public decision makers are supposed to design RES support schemes with a view to efficiently use electricity consumers' money (who are at the end paying for RES-E support), i.e., to obtain the greatest amount of RES-E generation per monetary unit of support. Therefore, the capacity factor is a central concern for both generators and manufacturers, but also for public decision makers (Boccard 2009, p.2679).

The importance of production efficiency for RES has led to some contributions on this topic, mostly focused on the analysis of capacity factors. Boccard (2009) and Yang et al. (2012) argued that wind energy generation in a year rarely exceeds 25% of its maximum capacity, and therefore there might be wind overcapacity due to wind farms idleness. In their analysis of wind deployment and generation in Spain, France, U.K. and Germany, Boccard (2009, p.2686) concludes that there is a lot of development in the most windy regions but also that intensive development takes place in sub-par regions. "Given that investment projects at the best sites have failed to materialise (or are unduly slowed), it might be useful and politically acceptable to introduce positive discrimination measures for sitting wind farms at the best sites". Yang et al (2012) analyse the causes of the large discrepancy between (high) installed capacity and (low) generation in China, which has even increased in recent years. This is despite the fact that this country is endowed with large wind resources, leading to a capacity factor of 16.3% between 2007 and 2010. The authors show that the best wind sites in China are often located far from the main load centers and that grid extension has not kept pace with capacity deployment, leading to many wind farms to remain idle.

However, despite the relevance of production efficiency from a social point of view, we have not found any contribution which aims to explain the reasons for the different capacity factors at the plant level, possibly because databases on renewable energy technologies at this level (such as the one for PV plants used in this article) are not publicly available. This paper shows that, in fact, policy-related factors, and particularly the level of support, may influence the location of PV plants.

Of course, transmission costs are an important element when deciding where to locate a plant. Locations may not be chosen in order to maximise electricity generation, but to minimise generation system costs, i.e., to minimise the direct costs of generation (the LCOE) plus the so-called indirect generation costs (transmission, back-up and profile costs, see Breischoft and

Held 2013). Intermittent generators should be encouraged to choose locations in a way that the value of the electricity produced is maximised and the system costs of generation are minimised. However, the focus of the empirical analysis in this article is on direct (and not indirect) generation costs. The reason is twofold. First, our database does not allow us to calculate these costs. Second, and most importantly, direct costs have traditionally accounted for a large share of total RES-E generation costs, whereas indirect costs have been very low. An abundant literature on RES-E consistently shows that the indirect costs represent a tiny fraction of the overall generation (system) costs with small penetration levels of intermittent RES (Breischoft and Held 2013, Gowrisankaran et al 2011, Gross et al 2006, Kopsakangas-Savolainen and Svento 2013, Holtinen et al 2011)[1]. Therefore, these indirect costs are unlikely to have been high in Spain in the period under study, given the small penetration of PV electricity (between 2.2% in 2009 and 3% in 2013).

Despite the abundant literature on the advantages and drawbacks of different RES-E support instruments (see EC 2013 and Mir-Artigues and del Río 2016 for in-depth reviews), the analysis of the productive efficiency of different instruments and design elements to support renewables has not received much attention in the past, in contrast to assessments of their effectiveness and support costs. FITs have generally been considered an effective instrument to encourage the deployment of RES-E plants (Ragwitz et al 2007, IEA 2011, Steinhilber et al 2011). However, it has also been found out that the total support costs of FITs, in the absence of capacity caps, can be much higher than with quantity-based instruments (Mir-Artigues and del Río 2016). For the specific case of PV, Pyrgou et al (2016) conclude that the growth of the PV sector in Europe could be attributed to the FITs but that "the generous tariffs supplied to the RES-E producers by the FITs led to extremely high profits to the RES-E producers" (op.cit. p.101). A main finding of the literature on RES-E support instruments is that the impact of different instruments depends as much on the choice of design elements as on the instruments themselves (Ragwitz et al 2007, IEA 2011).

FITs have often been considered problematic in terms of static efficiency on theoretical grounds. For instance, Borenstein (2011) argues that FITs do not encourage the choice of the cheapest technologies and locations. EC (2013) notes that setting appropriate remuneration levels and adjusting those levels overtime is a considerable challenge in FITs. However, the empirical literature on the productive efficiency of different RES-E support schemes, including PV, is very thin. Schmidt et al (2013) analyse the effects of feed-in tariffs and feed-in premiums on the location of wind farms in Austria with the help of an empirical optimization model and

[1] See Cerdá and del Río (2015) for a review of this literature.

show that, under a FIT, spatial diversification is incentivised. Del Río (2017a, 2017b) analyses the static efficiency of auctions for solar PV in Zambia and for renewables (including PV) in Mexico and shows that PV plants were not located in the places with the highest irradiation levels.

Regarding the particular case of the Spanish FITs for solar PV, their impacts on effectiveness (evolution of installed capacity) and support costs have been well analysed but their effects on the location of plants and the productive (in)efficiency of the regulation have not. For example, del Río and Mir-Artigues (2012, 2014) assessed the multifaceted nature of the different factors behind the PV boom in Spain taking place in 2007-2008 and the ensuing increase in support costs, but generation costs were disregarded.

This paper contributes to the analysis of this topic. Accordingly, it is structured as follows. An overview of the Spanish regulation for solar PV is provided in section 2. Section 3 describes the data and the model used for this study. The empirical results are provided and discussed in section 4. Section 5 concludes.

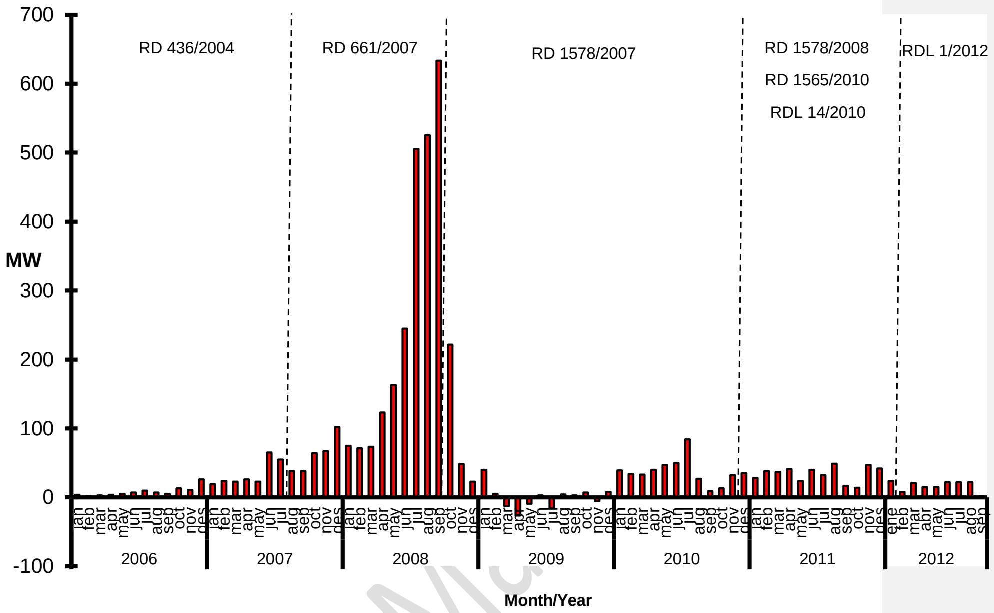
2. The feed-in tariffs for solar PV in Spain

The FIT for the support of RES-E generation in Spain was first applied in 1998 (Royal Decree 2818/1998). Solar PV developers were able to choose between either a fixed FIT adjusted annually or a fixed feed-in premium (FIP) on top of the electricity market price. Until 2004, PV deployment levels were stable but low, and remuneration levels were reviewed annually (del Río, 2008).

Royal Decree 436/2004 amended the RES-E support scheme in 2004. The RES-E sector had criticised the annual revision of support in Royal Decree 2818/1998, claiming that it was not transparent (del Río 2008). Under the new Royal Decree (RD), FIT levels were set as a percentage of the electricity price, or the "Average Electricity Tariff" (AET) and were revised every four years rather than annually. This system was regarded as a less arbitrary, more objective, stable and transparent method for setting support levels (del Río 2008).

Although RD436/2004 led to a more favourable treatment of solar PV technologies than the previous regulation, the solar boom in 2007-2008 was mostly a consequence of Royal Decree 661/2007. This RD, enacted in 2007, de-linked the FIT rate from the AET. PV installations could no longer choose between a FIP and a FIT, but were required to accept a FIT. Deployment increased substantially from April 2007 to August 2008 (see Figure 1).

Figure 1. Monthly installed PV capacity (MW).



Source: del Río and Mir-Artigues (2014). Note: Negative values are due to database corrections.

The exponential growth in solar PV deployment caused a parallel growth in the costs of the FIT. The share of PV in electricity generation in 2012 was low (around 10% of RES-E generation and 3% of overall electricity generation), but it accounted for around half of RES-E support since 2008. PV support skyrocketed from 194 M€ in 2007 to 990 M€ in 2008 and 2600 M€ in 2009.[2]

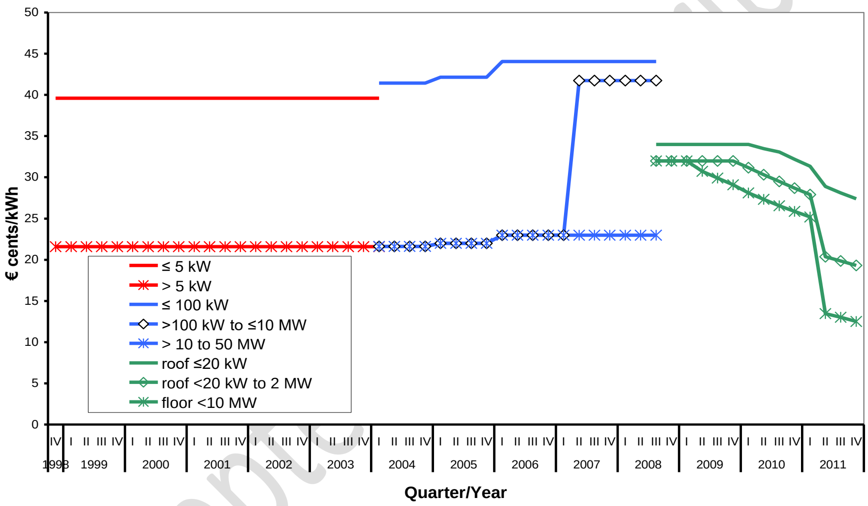
Several factors led to the boom. These were technological (falling manufacturing costs, capacity upgrades and increasing efficiency of the PV panels), financial (easy access to credit, favourable €/$ exchange rates and capital flight from housing) and administrative (fast-track permit provisions provided by regional authorities and poor coordination between regional and national authorities) (see del Río and Mir-Artigues 2014 for full details).

However, the main factors were policy-related. A key one was the fact that technology costs were decreasing (Roland Berger 2014) and FIT levels did not change to account for these cost reductions. Tariffs were designed to provide developers with an internal rate of return (IRR) for

[2]Net support costs are calculated as the overall FITs and FIPs paid to RES-E, minus the average wholesale price (in the case of FITs), and multiplied by the amount of GWh of RES-E being generated.

their projects of 5% to 9%. Although the government had set support levels to allow for a “reasonable” profitability of 7%, actual IRRs for projects in the best sites were between 10% and 15% (del Río and Mir-Artigues 2014). Tariffs had not increased significantly for small (<100kW) and large installations (> 10 MW) between 2004 and 2007, and those tariffs had not proven to be excessive. But the FIT rate for installations >100 kW and ≤10 MW almost doubled with RD661/2007 (Figure 2). In addition, the FIT of RD661/2007 was less risky and more attractive for investors, since support levels were no longer tied to electricity prices (as in RD436/2004). Revenue flows were more certain.

Figure 2: FIT levels for PV (€ cents/kWh), 1998–2011.



Source: del Río and Mir-Artigues (2014).

Two other policy aspects played a main role as drivers of the boom: the expectation of a change to a less favourable regulation and slow policy change. RD661/2007 stated that a new regulation with lower FITs would need to be approved within a year once 371 MW had been installed i.e., about 85% of the target for PV. Since this was reached in June 2007, a draft of the new regulation with significantly lower remuneration levels with respect to the current Royal Decree 661/2007 was made public in September 2007. This led to a rush of applications until August 2008 in order to benefit from the existing FIT.

By the time the new RD1578/2008 entered into force (in September 2008), 3,116 MW of PV capacity had already been installed (around 10% of RES-E and 2% of total electricity generation installed capacity in that year), compared to 544 MW at the end of 2007. The new RD introduced quarterly capacity quotas (caps) for each type of installation. This limited the amount of PV which would be eligible for support. Deployment of capacity determined tariff changes, which in turn determined quarterly capacity quotas (capacity corridors). Capacity under the quota was allocated to developers on a first-come, first-served basis and it was linked to the FIT level[3]. The capacity quotas reduced the number of projects which received financial support. Applications for 502 MW worth of solar PV plants were received, while only 155 MW were actually installed in 2009.

Controlling the growth in PV capacity and setting cost-containment mechanisms were priorities for the government once the size of the PV boom under RD661/2007 became obvious. This led to the approval of several new regulations (including Royal Decree 1565/2010 and Royal Decree Law RDL14/2010), which amended either RD661/2007 (regulating PV plants installed before September 2008) or RD1578/2008 (regulating plants installed after that date). The following measures were introduced: a maximum period over which support was available instead of it being open-ended (retroactively for existing solar PV plants), a cap on the number of operating hours that plants could deliver electricity (also retroactively for existing solar PV plants), a tighter legislation on repowering of solar PV systems, an electricity generation tax and a change in the updating tariff system.

A moratorium on new projects was imposed by RDL1/2012 in 2012 and a new RES-E promotion scheme, which involved a substantial rupture with the pre-existing system, was adopted in 2013/2014. The new scheme is retroactive, i.e., it applies to plants which were subject to either RD661/2007 or RD1578/2008. Three auctions under the new scheme have been organised in 2016 and 2017, with a total of 3,910 MW being awarded to PV projects. These plants will have to be built by December 31st 2019.

Some papers have analysed the impact of the aforementioned retroactive cost-containment regulations and the new regulation of the electricity sector in 2013/2014 on the profitability of PV plants deployed before 2008 (Mir-Artigues et al 2015, 2018, Lomas et al 2018), leading to the conclusion that those regulations had a considerable impact on such profitability levels.

[3] If less than 75% of the quota was met, then the pre-established FIT level would apply for the next call. If more than 75% of the quota was met, then the FIT level would be reduced according to a proportion set out in a predetermined formula (del Río and Mir-Artigues 2014).

3. Model and data

3.1 The model

In order to study the effects of deployment support (FITs) on productive efficiency and, more specifically, on the incentives to locate the plants on the sites with the best renewable energy resources, electricity generation from each PV plant is modeled as follows:

$$E_{it} = f(Z_{it}, T_{it}, I_{it-1}) \qquad [1]$$

Where *E* measures electricity generation (kWh) divided by the installed capacity (kW) of each plant. For the same installed capacity, a higher level of generation implies a better use of the capacity to produce electricity. *Z* is a binary qualitative variable on the zone where the plants are located, with 0 representing the zones with the lowest irradiation levels (zones 1 and 2) and 1 the ones with the highest irradiation (zones 3, 4 and 5) (see Table 1 and next subsection for further details). Obviously, plants located in zones 3 to 5 are expected to lead to higher electricity generation levels per unit of installed capacity than those located in zones 1 and 2. *T* is a dummy variable which identifies the type of installation. It takes the value of 1 for rooftop installations and 0 for ground-mounted plants. Finally, variable *I* is built as the ratio of the investment made in the PV plant and the total installed capacity of each plant (€/kW). The quality of the panels used in the PV plant is deemed a key factor to explain why the same kW of installed capacity implies a different investment level. It could be expected that higher-quality panels would be more expensive and, thus, a greater investment level would have a positive effect on the degree of utilization of the total installed capacity. Finally, year dummies are included in order to control for temporary effects.

Once logarithms are taken on the continuous variables, the following model is estimated:

$$LnE_{it} = \propto_i + \beta_1 Z_{it} + \beta_2 T_{it} + \beta_3 LnI_{it-1} + \sum_{j=4}^{8} \beta_j year + \epsilon_{it} \qquad [2]$$

Given that the variables *E* and *I* are measured in logarithms, parameter β_3 can be interpreted as an elasticity. A panel stochastic frontier model of equation [1] can be estimated in order to identify the degree of efficiency in the utilization of the capacity to produce electricity. This methodology allows decomposing the error term as follows:

$$\varepsilon_{it} = v_{it} - u_{it} \qquad [3]$$

Where ε_{it} is the composed error term, v_{it} is the measurement and specification error and μ_{it} is a one-sided disturbance that captures inefficiency.

Two assumptions have been made on the inefficiency term (see Belotti, 2013). Firstly, v_{it} and μ_{it} are independent and identically distributed across observations. Secondly, μ_{it} follows a half-

Commented [CP1]: U or nu

normal distribution, $\mu_{it} \sim N^{+}(0, \sigma_u^2)$ (Aigner, Lovell, and Schmidt (1977). However, traditional panel stochastic frontier methodologies do not distinguish between unobserved individual heterogeneity and inefficiency (Wang and Ho, 2010) and they may suffer from endogeneity problems (Kutlu 2010). The determinants of the production frontier and the two-sided error term may be correlated. According to Karakaplan and Kutlu (2017), endogeneity in stochastic frontier models may lead to inconsistency in the parameter estimations. In the specific case on this paper, improvements in operation over time and/or economies of scale and learning effects may impact the performance of the PV plants. Therefore, in order to identify the potential existence of endogeneity problems, we use the panel stochastic frontier methodology introduced by Karakaplan and Kutlu (2017) to examine the productive efficiency of the Spanish PV regulation. This method allows us to test and treat the potential endogeneity of the frontier and inefficiency variables (See Karakaplan and Kutlu, 2017 for methodological details).

The level of efficiency is estimated using the conditional method proposed by Jondrow et al. (1982) as follows:

$$Efficiency_{it} = E(u_{it}/v_{it} + u_{it}) = \frac{Observed\ production}{Frontier\ production} = e^{-u_{it}}$$

If the value of the ratio is 1, then the PV plants are fully efficient (100%). Obviously, the inefficiency level is higher the closer it is to zero.

3.2. Description of data

We use a panel database of 880 solar PV plants installed in Spain between 2002 and 2013. These plants represent about 95% of the population of all PV plants which were producing electricity as of 2013. This database was kindly provided by the Spanish PV Association (Asociación Nacional de Productores de Energía Fotovoltaica, ANPIER). It refers to plants which brought the Spanish Government to trial in the Supreme Court against the RD that reduced the annual number of hours of PV generation which were eligible for support in 2011, 2012 and 2013 (RDL 14/2010). These plants had been deployed under RD436/2004, RD661/2007 and RD1578/2008. For estimation and comparability purposes, we use the total number of plants (n=880) in the 2009-2013 period (t=5). The efficiency of a plant in electrical engineering is generally defined as the useful power output divided by the total electrical power input and, thus, the dependent variable in this paper (efficiency) is defined as the net electricity which is annually generated divided by the total installed capacity of the plant (kWh/kW)[4]. Table 1 provides the full definition of the dependent and independent variables and shows the descriptive statistics[5].

Table 1. Definition of variables and descriptive statistics.

Variable	Definition	Obs	Mean (std)
Dependent variable			
LnEE	Metric variable: Ln of net electricity generated yearly divided by total installed capacity (Kwh/Kw).	4,380	0.210 (0.295)
Independent variables			
Zone	Dummy variable: Solar irradiance zones in Spain 0: zones 1 & 2 - $H<3.8$ kWh/m2 & $3.8\leq H<4.2$ 1: zones 3, 4 & 5- $4.2\leq H<4.6$ & $4.6\leq H<5.0$ & $H\geq 5.0$	0: 205 1: 4,195 Total: 4,400	0.953 (0.211)
South	Dummy variable: South-Mediterranean or north region 0 North 1 South	0: 2,035 1: 2,360 Total: 4,395	0.537 (0.499)
Type	Dummy variable: Type of plant 0 Ground-mounted 1 Roof-top	0: 3,700 1: 690 Total: 4,390	0.157 (0.364)
Investment	Metric variable: Ln of monetary investment since the start-up of the plant until 2013, divided by the total installed capacity (€/Kw).	4,400	1.606 (0.770)

It is expected that the zone where the PV plant is located influences the efficiency of the plant. The irradiation zones in Spain were defined by the Technical Building Code in 2006. It classified the Spanish territory in five different climate areas according to their annual daily average solar irradiation (kWh/m2 on horizontal surface). The higher the irradiation of the zone, the higher the electricity generation per MW of installed capacity.

The type of plant (Type I and Type II) is included as a control variable. Type I PV installations are placed on roofs or facades of buildings for residential, services, commercial, industrial or agricultural use. Type I.1 installations have a capacity lower than or equal to 20KW and Type I.2 plants have a capacity above 20KW (and less than 2 MW). Type II PV installations are placed on the ground. They are generally infrastructures for solar PV farms with a maximum power of 10 MW.

The monetary investment accumulated since the start of operation of the plant until 2013 divided by the total installed capacity (€/kW) is included as an explanatory variable for the calculation of the panel stochastic frontier model. This variable allows us to control for PV cost

[4] The international standard ISO 50001 (ISO, 2011) defines energy efficiency as the proportion or other quantitative relationship between the result in terms of performance, services, of goods or energy and the entry of energy.
[5] For the stochastic frontier analysis, continuous variables are transformed into natural logarithms.

reductions in the last years. Additionally, year dummies from 2010 onwards are introduced in order to control for temporal effects (2009 is omitted due to collinearity issues).

4. Results and discussion

A panel production frontier estimation corrected for endogeneity problems is used to identify the differences in the productive efficiency of PV plants installed under different FITs in Spain. In order to check the sensitivity of our regression results to the choice of the different variables, we have replaced the Zone variable with a South-North dichotomous variable which includes all regions which are located south of Madrid and in the Mediterranean coast. Sensitivity analysis results are consistent with the baseline regressions (Table A1 and A2 in the Appendix).

The estimation results are presented in Table 2. Model EX refers to the model that ignores the presence of endogeneity, and Model EN represents the model that uses the Karakaplan and Kutlun (2017) methodology to tackle endogeneity. Evaluated at the mean values of variables, we cannot reject the hypothesis that the function has constant returns to scale at any conventional level. The η endogeneity test indicates that the stock of investment is exogenous and, thus, endogeneity should not be a concern. We find that the stock of the investment has a negative and significant effect on efficiency[6] for the plants under RD436/2004 but this effect is positive and significant for those under RD661/2007 and RD1578/2008. The effect is larger for plants under RD661/2007, which was the regulation providing the highest support for PV electricity generation.

Table 2. Estimation results.

Dep: LnEE	RD 436/2004		RD 661/2007		RD 1578/2008		ALL	
	EX	EN	EX	EN	EX	EN	EX	EN
Zone (Ref.0)	-0.015	-0.015	0.033	0.032	-0.143*	-0.148*	-0.060	-0.062
	(0.017)	(0.017)	(0.028)	(0.028)	(0.060)	(0.061)	(0.033)	(0.032)
Type (Ref. 0)	-0.255	-0.254	-0.113***	-0.113***	0.311***	0.309***	-0.067**	-0.069**
	(0.152)	(0.191)	(0.018)	(0.018)	(0.041)	(0.041)	(0.021)	(0.021)
Ln ($Investment_{t-1}$)	-0.022*	-0.023*	0.099***	0.097***	0.069***	0.065***	0.087***	0.081***
	(0.011)	(0.011)	(0.004)	(0.004)	(0.009)	(0.012)	(0.003)	(0.003)
2010	-0.008***	-0.008***	0.001	0.001	0.048	0.048	0.003	0.003
	(0.001)	(0.001)	(0.002)	(0.002)	(0.031)	(0.031)	(0.004)	(0.004)
2011	-0.003*	-0.003*	0.001	0.001	0.206***	0.207***	0.019***	0.019***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.031)	(0.031)	(0.004)	(0.004)
2012	0.001	0.001	0.004	0.004	0.292***	0.294***	0.028***	0.028***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.031)	(0.032)	(0.004)	(0.004)
2013	-0.003*	-0.003*	-0.004*	-0.004*	0.318***	0.321***	0.023***	0.024***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.031)	(0.032)	(0.004)	(0.004)
Intercept	1.212***	1.212***	1.031***	1.033***	0.123	0.132	1.055***	1.065***

[6] If the reader is interested in the inefficiency of each plant rather than on the efficiency level, the inefficiency coefficient can be calculated through the following expression: $inef_i=1-ef_i$

	(0.021)	(0.021)	(0.028)	(0.028)	(0.069)	(0.072)	(0.032)	(0.031)
Dep. Variable: Ln (σ^2_u) Constant	-0.009 (0.111)	-0.009 (0.111)	0.076 (0.058)	0.075 (0.058)	-2.703*** (0.260)	-2.701*** (0.260)	-0.051 (0.051)	-0.054 (0.051)
Dep. Variable: Ln (σ^2_v) Constant	-8.867*** (0.055)		-6.624*** (0.028)		-3.315*** (0.082)		-5.179*** (0.024)	
Dep. Variable: Ln (σ^2_w) Constant		-8.867*** (0.055)		-6.625*** (0.002)		-3.316*** (0.082)		-5.181*** (0.024)
η_1 (ln(Investment$_{t-1}$))		0.001 (0.007)		0.003 (0.002)			0.012** (0.004)	
η endogeneity test	F-stat = 0.01 p-value = 0.939		F-stat = 1.91 p-value = 0.167		F-stat = 0.25 p-value = 0.614		F-stat=9.68 p-value=0.002	
N	815	815	3175	3175	380	380	4375	4375
Log likelihood	1715.92	2771.19	3805.99	2944.62	39.18	-449.51	2759.72	668.60
Mean efficiency	0.3770	0.4099	0.3741	0.4060	0.8266	0.8378	0.3970	0.4291
Median efficiency	0.3536	0.3846	0.3470	0.3770	0.8587	0.8744	0.3716	0.4022

The level of efficiency ranges from 0 to 1. Table 3 provides the mean tests for differences in productive efficiency for each Royal Decree. The t tests show that those average levels are significantly different from zero in all the estimations.

Table 3. Mean test for differences in productive efficiency

	RD 436/2004	RD 661/2007	RD 1578/2008	Diff
EX	0.3930 (0.0014)	0.3773 (0.0012)		0.0157*** (0.0003)
	0.3930 (0.0014)		0.8980 (0.0011)	-0.5050*** (0.0017)
		0.3773 (0.0012)	0.8980 (0.0011)	-0.5207*** (0.0015)
EN	0.4253 (0.0014)	0.4090 (0.0013)		0.0163*** (0.0003)
	0.4253 (0.0014)		0.9030 (0.0010)	-0.4777*** (0.0017)
		0.4090 (0.0013)	0.9030 (0.0010)	-0.4940*** (0.0014)
Obs	4375	4375	4375	

*** Significance at 1%, ** at 5%, and * at 10%. The differences in the means and the standard errors on the differences have been estimated by running the corresponding paired t-test.

Table 3 allows us to compare the average efficiency for the three RDs being analysed. The efficiency range of the PV plants subject to RD436/2004 is 0.393 for the EX model and 0.4253 for the EN model. Regarding RD661/2007, the efficiency means are 0.3773 for the EX estimation and 0.4090 for the EN estimation, respectively. On the other hand, the average efficiency with RD1578/2008 is the highest of the three RDs, with a value of 0.8980 in the EX model and 0.9030 for the EN model.

The results of the t tests for all the cases analysed lead us to reject the null hypothesis that the efficiency means are equal. Thus, when net support (support levels minus generation costs) was the highest (RD661/2007), the efficiency was the lowest. In contrast, when support was lower, the inefficiency was substantially higher. This is probably the result of the degression design element which was introduced by RD1578/2008, whereby remuneration was reduced over time and was better adjusted to the downward evolution of technology costs, leading to a higher competitive pressure.

Therefore, our results suggest that relatively high administratively-set FITs without degression and capacity caps, in a context of sharp reductions in technology costs, did not encourage the choice of the best locations. Thus, instruments for RES-E support, but also design elements within instruments, should carefully be chosen in order to be effective and to minimise support costs, but also to encourage the choice of the best sites, i.e., to minimise (direct) generation costs.

Indeed, our results suggest that, even within FITs, some design elements may indirectly induce the choice of the best locations by adjusting support levels to generation costs. This puts more pressure on project developers to keep costs down and, thus, to search for the cheapest locations. One of this is the aforementioned degression. Under traditional degression, a pre-set reduction of support levels over time for new plants is established. This can be quite rigid since costs may evolve in unexpected ways, and the rate of reduction in support would not adapt accordingly. In contrast, under flexible degression, the reduction in support levels over time depends on the total installed capacity in a previous period (year, quarter or month): If the costs of new installations fall faster than expected and the growth in installations increases beyond expectations, the FIT is sharply reduced (EC 2013). Figure 2 shows that, despite substantial reductions in the costs of the technology between 2004 and 2008, FIT levels did not go down. Thus, profit margins (support levels minus generation costs) probably increased overtime, discouraging the search for the best locations. Degressive support would have provided such incentive to some extent.

On the other hand, capacity caps, in which only some capacity is eligible for support, would have reinforced that incentive. Capacity caps probably lead project developers to make a selection of the portfolio of projects that they would like to be eligible for the FIT, compared to

FITs without capacity caps. Notwithstanding, the first-come-first-served basis of these capacity caps in order to be eligible for support would still induce less competitive pressure in administratively-set FITs than in auctions.

Indeed, our results confirm that flexible degression with capacity caps encouraged the choice of better locations. These design elements were adopted in RD1578/2008 and the efficiency range with RD1578/2008 is the highest of all three regulations.

Two important remarks are worth making in this context. First, it should be taken into account that, in 2010, RDL14/2010 retroactively implemented a cap on the operating hours which were eligible for support for those plants which had been installed under RD1578/2008 and RD661/2007. Any electricity generated within the cap would be remunerated at the relevant FIT rate, whereas electricity generated above the cap could only be sold at the wholesale electricity price. It could be argued that this cap encouraged PV plants to generate only up to the maximum hours which would be eligible for support. If this was so, then generation levels for plants under RD661/2007 and RD1578/2008 would not only be related to the choice of locations induced by those two regulations, but also by the cap established in 2010. However, such retroactive regulation obviously did not affect the decision to locate the plants, which was taken before RDL14/2010 entered into force. Furthermore, the efficiency was highest for plants under RD1578/2008, precisely the ones for which RDL14/2010 implemented greater reductions of support in the zones with higher solar irradiations levels.On the other hand, it could be argued that, despite higher support levels, technology-specific FITs do not eliminate the incentive to use the best locations. Whatever the support level is, using a better location involves a greater benefit (revenues minus costs) for RES-E generators. This is so unless a geographically-specific stepped FIT, with levels differentiated per location, was implemented. Under stepped FITs, higher support levels are provided to plants located in places with worse solar resources in order to induce a more geographically even distribution of PV projects across the territory (see, e.g., Ragwitz et al 2007) and the incentive to use the best locations is partly lost[7]. This stepped FIT was not used in Spain. While, even without a stepped FIT, RES-E investors have an incentive to locate the plants in the best places, the existence of high profit margins, even in the worse locations, reduces the pressure to deploy the plants in those sites.

[7] The incentive to locate in the best places is only partly lost (i.e., not totally eliminated) with respect to the absence of differentiation of support levels per location if the support level minus the costs in the best locations are not below the benefits in the worst locations.

5. Conclusions

This article has identified the impact of successive FITs on the location of PV plants in Spain with the help of a unique dataset of plants and a panel stochastic production-frontier model. It has been found out that those FITs providing higher support levels have not encouraged the location of PV plants in the best sites. When net support was the highest (as under RD661/2007), the efficiency was the lowest. In contrast, when support levels adjusted to the evolution of technology costs and, therefore, went down (as with RD1578/2008), the efficiency substantially increased.

There is a clear opportunity cost in having solar PV plants located in places with low irradiation levels. Our results suggest that instruments and design elements should be adopted which allow the best locations to be chosen, while simultaneously minimising the transfer from consumers to RES-E producers. It is often argued that administratively-set FITs, such as those implemented in Spain between 1998 and 2013, put less competitive pressure on project developers than other instruments, e.g. auctions. The later are considered to better adjust support levels to the evolution of the costs of the technology over time, leading to higher efficiency levels (including the choice of the best locations)(del Río and Linares 2014, European Commission 2013). However, this paper suggests that it might not be only an issue of instrument choice, but one of design element choice as well. Although it has often been mentioned that other instruments (e.g., auctions) are more likely to enhance the production efficiency of RES support, our results show that the conclusion that FITs do not encourage the deployment of RES plants in the best locations strongly depends on the design elements adopted in this instrument. Indeed, some design elements in FITs, such as degressive support and capacity caps eligible for support, would induce a better choice of locations.

Degression in FITs leads to lower support levels over time and, thus, encourages project developers to choose the best sites in order to increase their profits. Capacity caps add an element of scarcity to the scheme, which also encourages the deployment of plants in the places with the lowest costs. Neither FIT degression nor capacity caps were adopted in RD661/2007. Our results show that, when they were implemented, as in RD1578/2008, higher efficiency levels resulted. Countries using FITs to support the deployment of renewable energy technologies are advised to adopt these two design elements if they aim to optimise production efficiency and minimise direct generation costs. Our results suggest that design elements which provide more support for the deployment of plants in places with worse renewable resources (as with stepped FITs) may have detrimental effects on production efficiency. However, those stepped FITs may be useful for other reasons (e.g., in order to encourage locations close to consumption centers and minimise system costs).

Some limitations of this research can be highlighted suggesting fruitful avenues for further research. First, the exact impacts of the retroactive changes on the efficiency levels have not been analysed. Therefore, future research should be devoted to disentangling the impact of this factor (particularly, the limitation of generation hours which are eligible for support). In addition, this paper focuses on direct generation costs, which is only one of the components of systems costs. Indirect costs such as balancing, profile and grid costs (Breitschopft and Held 2013) should also be considered in order to identify whether the above regulations were also inefficient from the point of view of system costs. Our paper disregards the fact that system costs may be minimised under a specific regulation even if the best sites are not chosen, i.e., even if direct costs are not minimised. However, the small penetration of PV over the period analysed suggests that, as mentioned above, those indirect costs are likely to be very small and, thus, that the focus on direct costs is correct and justifiable from the point of view of system costs.

Other avenues for future research can be suggested. Empirical analyses on the comparative productive efficiency of different instruments (i.e., auctions vs. administratively-set FITs) should be performed. Further research effort should be devoted to analyse which design elements may enhance the productive efficiency of promotion in other, still maturing technologies which need public support, focusing on the experiences with FITs in other countries.

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APPENDIX

Table A1. Sensitivity analysis

Dep: LnEE	RD 436/2004		RD 661/2007		RD 1578/2008		ALL	
	EX	EN	EX	EN	EX	EN	EX	EN
SouthNorth	-0.023	-0.023	-0.163***	-0.163***	0.134**	0.134**	-0.014***	-0.012***
(Ref.0)	(0.017)	(0.017)	(0.018)	(0.018)	(0.047)	(0.047)	(0.002)	(0.002)
Type (Ref. 0)	-0.268	-0.268	0.012	0.012	0.310***	0.309***	-0.001	-0.003
	(0.179)	(0.164)	(0.021)	(0.021)	(0.041)	(0.041)	(0.003)	(0.003)
Ln (Investment$_{t-1}$)	-0.009	-0.009	0.099***	0.097***	0.070***	0.066***	0.053***	0.049***
	(0.018)	(0.019)	(0.004)	(0.004)	(0.009)	(0.012)	(0.003)	(0.003)
2010	-0.008***	-0.008***	0.001	0.001	0.048	0.048	-0.001	-0.001
	(0.001)	(0.001)	(0.002)	(0.002)	(0.031)	(0.031)	(0.001)	(0.001)

2011	-0.003* (0.001)	-0.003* (0.001)	0.001 (0.002)	0.001 (0.002)	0.206*** (0.031)	0.207*** (0.031)	0.003*** (0.001)	0.003*** (0.001)
2012	0.001 (0.001)	0.001 (0.001)	0.004 (0.002)	0.004 (0.002)	0.291*** (0.031)	0.294*** (0.031)	0.005*** (0.001)	0.006*** (0.001)
2013	-0.003* (0.001)	-0.003* (0.001)	0.004 (0.002)	0.004 (0.002)	0.318*** (0.031)	0.320*** (0.031)	0.003*** (0.001)	0.003*** (0.001)
Intercept	1.215*** (0.021)	1.215*** (0.022)	1.244*** (0.024)	1.246*** (0.024)	-0.169** (0.063)	-0.164* (0.063)	-0.056*** (0.005)	-0.051*** (0.005)
Dep. Variable: Ln (σ^2_u) Constant	-0.009 (0.111)	-0.009 (0.111)	-0.024 (0.058)	-0.025 (0.058)	-2.728*** (0.265)	-2.727*** (0.265)	-5.402*** (0.062)	-5.416*** (0.062)
Dep. Variable: Ln (σ^2_v) Constant	-8.868*** (0.055)		-6.622*** (0.028)		-3.320*** (0.083)		-9.003*** (0.030)	
Dep. Variable: Ln (σ^2_w) Constant		-8.868*** (0.055)		-6.622*** (0.028)		-3.321*** (0.015)		-9.010*** (0.030)
η_1 (ln(Investment$_{t-1}$))		0.000 (0.007)		0.003 (0.002)		0.008 (0.015)		0.010*** (0.002)
η endogeneity test	F-stat = 0 p-value = 0.972		F-stat = 1.92 p-value = 0.165		F-stat = 0.28 p-value = 0.595		F-stat = 24.53. p-value = 0.000	
N	815	815	3170	3170	380	380	2912	2912
Log likelihood	1716.17	2768.01	3828.53	2966.49	40.3	-456.57	7758.28	9756.16
Mean efficiency	0.3781	0.4109	0.3915	0.4234	0.8278	0.8388	0.9660	0.9685
Median efficiency	0.3563	0.3871	0.3867	0.4159	0.8304	0.8453	0.9661	0.9689

Table A2. Mean test for differences in productive efficiency of the sensitivity analysis

	RD 436/2004	RD 661/2007	RD 1578/2008	Diff
EX	0.3620 (0.0008)	0.3685 (0.0007)		-0.0065*** (0.008)
		0.3685 (0.0007)	0.8353 (0.0012)	-0.4733*** (0.0018)
	0.3620 (0.0008)		0.8353 (0.0012)	-0.4668*** (0.0016)
EN	0.3922 (0.0008)	0.3982 (0.0007)		-0.0060*** (0.0008)
		0.3982 (0.0007)	0.8439 (0.0012)	-0.4456*** (0.0015)
	0.3922 (0.0008)		0.8439 (0.0012)	-0.4517*** (0.0017)
Obs	2912	2912	2912	

*** Significance at 1%, ** at 5%, and * at 10%. Only observations from 2009 onwards are used. The differences in means and the standard errors on the differences are estimated by running the corresponding paired t-test.