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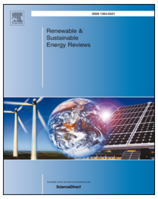

Economic and environmental analysis of a residential PV system: A profitable contribution to the Paris agreement

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ABSTRACT

The aim of this paper is to analyze the economic and environmental aspects of installing PV facilities for residential electricity users. This paper explores, in a conservative approach, the installation of a PV capacity to compensate the consumption with the production for each moment, never feeding electricity into the utility network and without storage.

The approach proposed is illustrated by applying different power PV capacities in alternative locations (Marseille, Madrid and Seville), using the hourly demand provided for the smart meters. Combining the load curve of each user, the irradiation and PV production of each location, the cost of equipments, the hourly emission in the whole market, the variable price of electricity for residential users and the energy needs to build a PV facility. The model calculates, for each individual the optimal PV power to install and the emissions avoided. The results show that, with the current cost of the PV facilities and variable prices of electricity, the PV are, from an economic and environmental point of view, profitable in all the locations analyzed. This initiative will be more profitable for private investors and, additionally, for the environment in the next three years. A massive installation of these facilities in Spain and France will contribute to achieving their Nationally Determined Contribution (NDC) of the Paris agreement (COP-21), fulfilling, in Spain, the current legal restrictions.

1. Introduction

One of the most frequent concerns that families have always had is about the amount of their electricity bill. More recently, the global warming matter has been added to the economic issue, with people asking also what we can do to contribute to reduce it. In this sense, the 2012 Energy Efficiency Directive (2012/27/EU) established three key targets (20% cut in greenhouse gas (GHG) emissions from 1990 levels, 20% of EU energy from renewable sources and 20% improvement in energy efficiency) giving a set of binding measures to reach this level of energy efficiency by 2020.

A right road map to reach 20% of EU energy from renewable energy sources (RES) might include self-consumption of electricity by households. From their point of view investment in photovoltaic (PV) energy can be motivated by two reasons: the economic profitability and the environment issue. Focusing on economic arguments the favorable recent evolution of the costs of the PV facilities makes their installation at the residential level present a positive evaluation that is both economic and environmental [7].

Estimations of the annual worldwide production of electricity produced by PV systems between 1955 and 2010 by Breyer and Gerlach [5] showed an average annual growth of 45% over the last 15 years. But this growth rate is naturally very different from one region to another. In particular, China plays a key role in this growth as it has been the first producer of the World since the beginning of 2016 [32] with a total of 63 GW of PV installation and the highest growth rate. Besides, this country is also very important in the solar market because the large majority of the panels are manufactured there - according to Fu et al. [17], 90% of Chinese PV products depend on international markets. Fig. A.1 in the Annex A illustrates this rapid growth in the last decade for solar power as well as for wind energy.

The main reason for this rapid and considerable growth lies in the technological improvements that allowed a strong decrease of the costs. Scientists characterize this reduction by the learning rate which is worth 20% in solar power ([25] and [2]). This learning rate is obtained by plotting in a log-scale the evolution of the price of a PV module

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against the global cumulated number of PV installations; the slope of the linear curve in this plan yields the learning rate, in this case, 20%. Bloomberg New Energy Finance (2014) [4] gives us an illustration of this decrease of the costs by estimating that they have declined from around US$ (2013) 80 per watt in 1976 to less than US$ (2013) 1 per watt in 2013 [52].

An additional economic argument that favors PV investment came from the Levelized Cost of Electricity (LCOE). This is defined as the cost that, if assigned to every unit of energy produced by the system over the lifetime period, will equal the total lifetime cost when discounted back to the base year [3]. This tool is largely used in the scientific literature to analyze the costs of the RES, in particular, to evaluate grid parity. In the solar power context we are here interested in, grid parity can be defined as the intersection of the price of the electricity generated by a PV system and the price of conventional electricity production [25]. The LCOE has also decreased over time and is planned to keep doing so in the next decades. Celik et al. [10] conducted a research taking a PV system of 120 W with a total cost of 1900 US$. Mokhtari et al. [34] analyzed the optimal size of a combined PV-Storage for a Grid-connected residential building taking a cost of 400 US$ for 100 W for the PV part. Hartner et al. [21] focused on Austria for the years between 2008 and 2013. In their data the learning curve made fixed cost to decrease from 5265 $/kW to 3981 $/kW. Gonzalez et al. (2015) [18] conducted a similar research for the Spanish case taking 3800 $/kW as the reference value. Chel et al. [9] estimated the cost per unit of electricity generated by PV system installed in New Dehli varying in a range from 46 US cents/kWh to 57 US cents/kWh. Majid Alabdul Salam et al. [30] calculated 56.1 US cents/kWh as the cost of energy for a similar system in Oman. Hernández-Moro and Martínez-Duart [22] have carried out an extensive study on the future evolution of the solar LCOE in United-States. They estimated that for 2010 it was around 40 US cents/kWh and that it will fall to approximately 10 US cents/kWh by 2050. Rahman and Nordin [41] found that 14 US cents/kWh was the Cost of Energy for the optimal size of a residential PV system in Malaysia but including batteries in it.

Despite the emerging literature dealing with PV cost evolution, to the best of our knowledge the literature has not analyzed the problem from the individual (residential client) point of view. However, there exist software solutions as that help to optimal sizing PV system but acts as a black box being outside the literature analysis (see at www.homerenergy.com/ Homer simulation tool developed by NREL). Reason for the scarcity of research focused on residential clients is mainly due to it not having been possible until now to carry out this study because it is necessary to have information about the hourly consumption of each customer. This can only be possible if smart meters are in complete operation. These meters provide an amazing amount of information that can help us make decisions to shift consumption. It might be borne in mind that one of the binding measures included in the 2012 Energy Efficiency Directive (2012/27/EU) was that, at least, 80% of consumers should have smart metering systems in 2020. It is anticipated that all 15 kW consumers in Spain will have been fitted with smart meters before the end of 2018 (Spanish Ministry of Industry, 2007 [47]).

Environmental reasons could also make costumers move to invest in PV energy systems. Life Cycle Analysis (LCA) and carbon footprint aim at determining if solar modules are as eco-friendly. The literature on PV's LCA approach has been also emerging: Raugei and Frank [42], de Wild-Scholten [11], Fthenakis [16] and [14,15]. For RES LCA this is generally done by analyzing the energy payback time (EPBT) which refers to the time, measured in years, required for a system to compensate for the energy used for its production. It is particularly adapted for solar power since the manufacturing process of the modules is the only energy-consuming step of their lifetime. The EPBT value varies in a significant way depending on where the PV system has been manufactured and where it is installed. If the same modules are mounted in Germany and in Malta, this will be much higher in the first case because there is less irradiation and therefore less annual production. Consequently, we can find a large range of values in the literature, but a significant decrease is certainly observed over time. Hunt [24] estimates the EPBT for terrestrial mono-crystalline silicon at 12 years. In their literature review, Fu et al. [17] inform that more recent studies value this to be between 1.5 and 7.5 years. The results of their own work give an EPBT between 2.2 and 6.1 years for modules manufactured and installed in China. Peng et al. [38] lead a study on the variation of the EPBT with regards to the type of modules: for thin film PV systems, monocrystalline silicon and high concentration cells, this is 0.75–3.5 years, 1.7–2.7 years and 0.7–2.0 years, respectively. Despite of its extended use in scientific papers a comment need to be made on EPBT closely related to EROI (energy returned on energy invested) because it has been the subject of strong disputes ([40], chapters 1 and 5).

A second indicator largely used in the literature is the amount of equivalent CO_2 which is emitted for each kWh generated. During its functioning period, a PV system does not use any energy nor does it release emissions; the unique production source of CO_2 is due to its manufacturing process. As for the EPBT, the amount of equivalent CO_2 depends on the location of the installation and the fabrication. Stylos and Koroneos [49] contemplate various scenarios for the PV market (efficiency improvement, changes in the raw materials, and so on) and find emissions ranging from 12 to 55 g CO_2/kWh. Mulvaney [35] obtains similar results, with estimations at 32 g CO_2/kWh and 68 g CO_2/kWh for Europe and China respectively. The Parliamentary Office of Science and Technology (2006) [36] evaluates it at 35 g CO_2/kWh for Southern Europe. In any case, all these values stay way lower than the equivalents for electricity generation from fuel or coal. For instance, a diesel generator provides an output emission of 922 g CO_2/kWh [49].

This paper makes two main contributions. The first is to define a methodology that, using the information provided by the smart-meter for each user and the irradiation of each location, calculate its optimum PV power that each individual customer should install economically, based on their time load curve and geographic position (the irradiance will depend on this) and the variable price of energy for the residential consumer. The second refers to the contribution of each installation to the reduction of CO_2 emissions, taking into account how much the emissions of the latest technology entering the wholesale market are. The application is made to some real and characteristic cases in Spain and France, as well as an estimation of what the contribution to the National Objectives of the Paris Agreement (COP-21 2016) could be if the solution proposed were applied in a massive way. The choice of Spain and France as a study case is due to the two countries being comparable in terms of irradiation, others key indicators as Total Primary Energy Sources/GDP (0.09 toe/thousand 2010 US $ -France- and 0.08 –Spain-), CO_2/GDP (0.1 kg CO_2/capita –France- and 0.17 –Spain-) [27], above all, having distinct electricity generation systems. Figs. A.2 and A.3 in the Annex A illustrate both systems showing the order in which different power technologies provide electricity to the pool market.

The European Union submitted a shared Intended Nationally Determined Contribution (INDC) in the context of the Paris Agreement which targets at least a 40% domestic reduction in GHG emissions by 2030 compared to 1990 and up to a 75% reduction by 2050. After signing the Paris Agreement, the INDC became the NDC. France and Spain will be studied as they have been the common thread of this whole paper. The point here is to know how much of these commitments could be reached just by installing PV systems such as the one described in this paper.

The rest of the paper is organized as follows. Section 2 offers some relevant notes from the previous literature on the PV costs and emissions evolution. Section 3 describes the model proposed for optimizing the PV power at the residential level in an easy way, whilst in Sections 4 and 5, the results and discussions are presented. Finally, Section 6 offers the main conclusions.

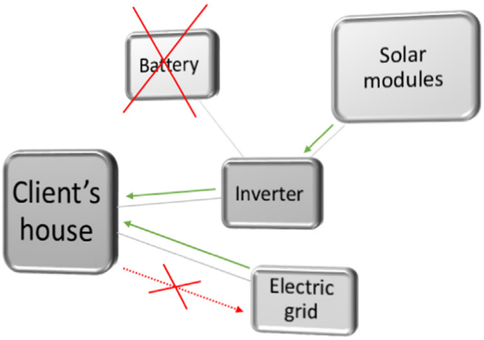

Fig. 1. Diagram of the whole PV system.
Source: own elaboration

2. Method

The optimization model gives us the peak capacity required to maximize the benefits of the installation in function of its geographical position and the local electricity price. The study considers the case of a typical dwelling wishing to install a PV system, either on the roof or on a structure separated from the building. The Spanish legal framework on electricity self-supply contemplates that some of the electricity produced is self-consumed. The legislation assumes that the energy produced is consumed by users close to the installation and does not affect the medium- and high-voltage connection nodes [31,46,6]. This system would only be used for self-consumption and no energy storage is envisaged, thus the house would still be connected to the grid, but part of the daily electricity demand would be fulfilled by the solar modules (see diagram in Fig. 1). It is a quite conservative model, both for the profitability evaluation and for the estimation of the environment impact. Indeed, the majority of the works published on these issues consider that the PV system includes an storage system allowing the consumption of electricity even during night hours, and/or that a certain amount of the production is sold back to the grid ([10,34]; Tremeac Meunier [53]). However, these two considerations increase the cost of the initial investment and the complexity of the project, especially in terms of the procedures to legalize the installation, the whole permit process being long and tedious. This is why we have chosen to remain with a basic system. Finally, the geographic context of this study is Southern France and Spain, two areas that are comparable in terms of irradiation and standards of living, but that will present some slight differences when it comes to investing in solar energy.

The main problem of solar energy is that the production profile of the PV system does not meet the shape of the load curve (see Fig. 2). The former is similar to a Gaussian distribution with a peak at midday, whereas the latter shows two peaks corresponding to lunchtime and evenings. Of course, both of these curves are dependent on the season. During summer there are more sunny hours and the irradiation is stronger, which means the Gaussian is higher and wider. The load curve always maintains a similar profile but it is higher or lower depending on the seasonal electricity needs. The case displayed in Fig. 2 is for irradiation and demand in Madrid area during a typical working day of March 2017. The load curve, corresponding to an average Spanish household, shows two representative peaks, one at midday and the other one around 8–9 p.m., mainly linked to lunch and dinner time.

Overlaying these two curves make two interesting areas appear: the losses which correspond to the electricity generated but not consumed (because it is produced at a moment of low demand) and the useful energy which is the really valuable electricity.

In Fig. 2, this useful energy is calculated for an individual consumer (smart meters installed), for one day (March 15th, 2017) and one place (Madrid), having a PV facility of 1.5 kWp, but to calculate the annual saving, we have to estimate this value for all the days of the year because the demand and the generation will be different depending on the season of the year.

As a result of the increased installed power of the photovoltaic system, the energy produced will rise proportionally, although due to the forms of the demand and generation curves, the usable energy will augment very little from a certain value. Fig. 3 shows the demand and generation for one day of March in Madrid for different values of PV power.

It does not make sense to calculate these values for a given day. In order to analyze the effect of the increase of usable energy by increasing the installed PV power, it is necessary to estimate the annual computation, as shown in Fig. 4.

2.1. Optimal PV size and profitability

The optimization process aims at finding the right capacity that allows the best compromise between these two quantities (PV size –investment- vs. useful energy –savings). Indeed, a higher capacity generates more useful energy but is also more expensive, resulting in a threshold beyond which it is not worth installing more solar modules

The method consists of calculating the Net Present Value (NPV) of the PV system in each case and selecting the capacity with the highest one. Obviously, the NPV depends on the useful energy but also on the electricity price, as the benefits of the project only come from the savings in the electricity bills which correspond to the useful energy multiplied by the price of a kWh bought on the grid. For this former price, we have to consider the variable of electricity price for final users. Indeed, a client investing in a PV system will reduce his/her consumption from the grid but will stay connected to it and will keep

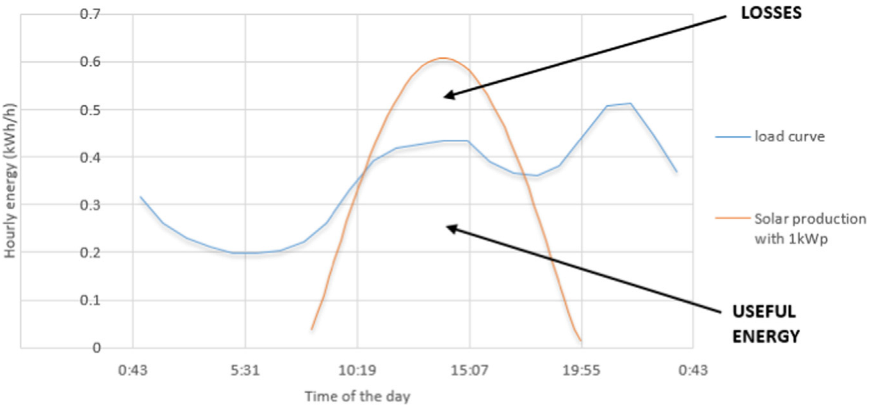

Fig. 2. Intersection between the daily profile of the domestic demand and the solar irradiation, data for Madrid area during a typical day of March 2017 for an average Spanish consumer.
Source: BOE, JRC European Commission and own elaboration

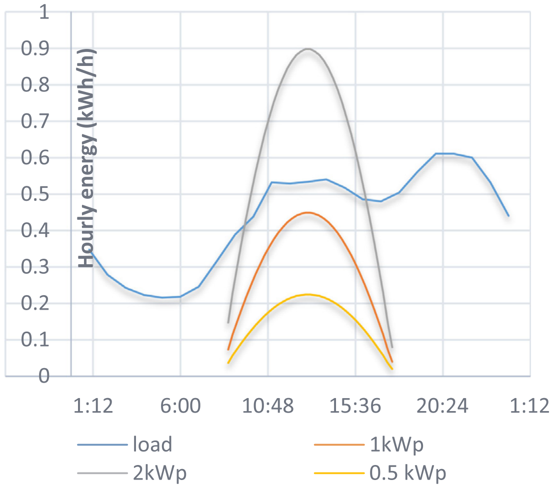

Fig. 3. Demand and production for different values of power installed in Madrid on March 15th, 2017.
Source: Own elaboration

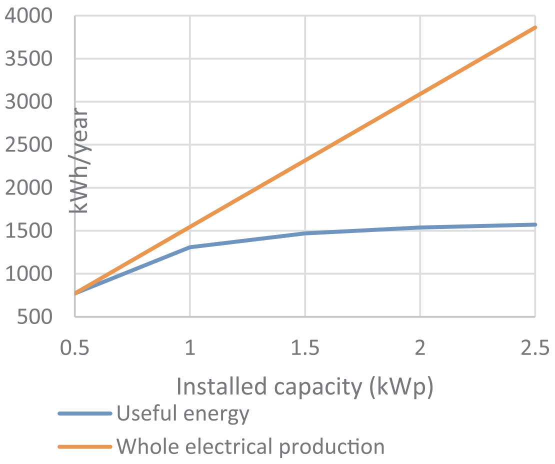

Fig. 4. Difference between useful energy and direct production from the PV system in function of its capacity, data for Madrid area on March 15th, 2017.
Source: own elaboration

buying electricity from it (during night hours and when the solar production is not enough to meet the demand). Therefore, this client cannot reduce the fixed costs relative to his/her contract (hiring of the meter, contracted power and cost of commercialization) but only the costs linked to the quantity of energy consumed.

Finally, the Weighted Average Cost of Capital (WACC) considered in the value is 0%, which is the same as considering that the investment made by the individual has no cost of opportunity. This choice was made because the amount of money invested is quite low, thus, the client would not necessitate a credit nor would change his/her way of life in the case of carrying out the investment. Many governments are offering public aid to help to finance these investments. This generally consists of loans without financial costs. Additionally, expansive monetary policy measures developed by the European Central Bank since the beginning of the financial crisis in 2008 have lowered interest rates near to zero values in a price stability context. The above mentioned arguments make a 0% discount rate credible in the long run.

The model will present better results the higher the irradiation in the selected location and the greater the variable final price of the electricity that the consumer bears.

2.2. *Assessment of CO_2 emissions avoided*

Once the optimal size of the PV facility for the selected user has been chosen, the model estimates its environmental impact in terms of CO_2 emissions avoided.

Consuming electricity from solar energy instead of from the grid reduces the marginal emissions corresponding to the latest technology to enter the electricity generation system. Therefore, the avoided emissions of CO_2 comes from the emissions rate of this latest technology multiplied by the amount of energy produced by the PV system.

To calculate the level of emissions avoided in each case, it is necessary to start from the reduction of hourly demand (usable energy), and compare this with the marginal generation technology of each wholesale energy market (carbon, fuel, combined cycles, etc.). The emissions avoided by each installation will be calculated by multiplying the usable energy by the emissions corresponding to the marginal generation technology of the wholesale market, and adding this up for all the hours of the year.

Once the CO_2 emissions avoided by each user and for each location are known, this value is compared with the emissions necessary for the production of the installation, which are taken from international references and will depend on where the photovoltaic installations have been manufactured.

3. Data

There are six sets of data that must be known to feed the model:

- Hourly consumption.
- Hourly PV production.
- PV equipment.
- Variable electricity price for residential users.
- Wholesale market performance.
- Energy and emissions to manufacture and install each solar installation

The method is applied for the cases of France (Marseille) and Spain (Seville and Madrid). The Marseille area has been chosen for being representative of Southern France (the Center and Northern parts of the country have a climate which is too different to be included in the same study). For Spain, two areas are chosen to illustrate the influence of distinct irradiation: Seville in the South and Madrid in the Center (the Northern part was also studied but it gave results identical to what was found for the Center). Data from these locations have been selected for the former points.

The hourly consumption of each user depends on their habits and the possibility of accessing other sources of energy. Until a few years ago, the information on electricity consumption was very limited, reduced for residential consumers to a record of energy consumed every two months.

The introduction of smart meters has meant an increase in five orders of magnitude in the information available for each user. For our analysis, the standard Spanish hourly profile has been taken from the Ministry of Industry, which calculates the annual energy percentage by one for each of the 8760 h of the year. To estimate the hourly consumption of a typical user, we simply multiply by the average residential consumption. In the Spanish case this amounts to 3250 kWh.

In the case of France, no public data of hourly energy consumption profiles are available so the data were calculated from a sample of real time curves provided by the ERDF anonymously, taking into account that the average residential consumption in France is 4250 kWh, probably due to higher heating needs and a higher standard of living.

The irradiation curve (hourly PV production) is obtained thanks to an online tool from the Joint Research Centre-JRC- European commission (Súri et al., 2007 [50]) which provides the local irradiance for each month and for each geographic position within Europe. This tool

Table 1
Price function for the whole PV system.
Source: [21]

Component	Price (€)
Module 250 W	125
Inverter[a]	600
System of control	300
Installation	500
Structure	300
Total	**1700 + 125*N**

[a] Although the cost of inverters increases with their size, it can be considered constant for the range in which we are moving (0.5–2 kW). It would be different if we explored a much greater range.

not only provides irradiation time for each given location, but for each production technology PV (fixed axle or dual axis) it estimates the orientation and optimal angle and its hourly production. Assuming that, for the sake of simplicity, the PV installations are fixed (simpler), the tool provides the hourly production curves for the selected sites (Marseille, Madrid and Seville). The information for PV equipment investment has come from Guisado-Falante and Lillo-Bravo [20] and is summarized in Table 1.

Since both France and Spain are members of the European Union, and transport costs do not vary significantly between the three sites, the costs of PV equipment have been considered the same in all cases. Moreover, the price of the equipment, which represents the initial investment, have been evaluated with a price function that has a fixed term and a variable term depending on the capacity installed. Table 1 explains this function giving the price of each component. These prices correspond to the lowest public ones existing on the market. However, they do not correspond to the first tariffs that appear on the internet since these former ones, in general, include a kit that makes it more expensive. The inverter represents an important part of the investment and has a lifetime of only 10 years. Consequently, three inverters will be bought over the life of the whole system (200 × 3). The final function obtained is 1700 + 125 *N where N stands for the number of 250 W modules required for the system. For instance a 2 kWp installation is worth 1700 + 125 * 8 = 2700€.

The electricity price for residential user's variable is evaluated in order to further determine the amount of money a customer could save on his/her bill by installing solar panels, and this sum of money will not depend on the average cost but on the marginal cost. Table 2 shows an example of a standard residential electricity bill in Spain from Sancha (2012) [45].

From the same source, the differences between the average prices for different countries are shown in Table 3.

To contrast the Spanish case, this data has been compared with the current offers of some suppliers for the energy components plus taxes. The data are shown in Table 4.

Table 2
Detail of an electricity bill in Spain.
Source: Sancha (2012) and own elaboration

Concept	Description	Amount
Energy	(1) energy price	0.067 €/kWh
Energetic systems and policies	(2) access toll to energy	0.064 €/kWh
	(3) toll relative to the contracted power	16.630 €/kW/year
	(4) capacity cost	0.011 €/kWh
	(5) commercialization cost	4€/kW/year
	(6) cost of hiring the meter box	0.540 €/year
Taxes	(7) electricity special taxes (Defined by the Ministry of Industry)	4.864%*1.051*[(1) + (2) + (4) + (5)]
	(8) VAT	18%*[(1) + … + (7)]

Table 3
Difference between average and marginal cost, price in €/kWh.
Source: Sancha (2012) and own elaboration

	Average price	Marginal price	Difference
Spain	0.22	0.18	**19.4%**
France	0.15	0.12	**19.0%**
Portugal	0.21	0.17	**16.9%**
Italy	0.26	0.22	**17.5%**

Table 4
Electricity 2016 retail prices offered by different companies, prices expressed in €/kWh.
Source: [12] and own elaboration

	Energy term	Electricity special taxes	VAT	Retail price
Goiener	0.137	0.007	0.026	0.170
Gesternova	0.118	0.006	0.022	0.146
Gas natural fenosa	0.135	0.007	0.026	0.167
EDP	0.120	0.006	0.023	0.149
Viesgo	0.170	0.009	0.032	0.211
Iberdrola	0.130	0.007	0.025	0.161
SOM energía	0.124	0.006	0.023	0.154
Holaluz	0.123	0.006	0.023	0.153
Endesa	0.140	0.007	0.026	0.174
Pepeenergy	0.112	0.006	0.021	0.139
Average	**0.131**	**0.007**	**0.025**	**0.162**

For all the above mentioned, the savings considered for the analyses proposed have been 0.16 and 0.12 €/kWh for Spain and France respectively.

Table 5 provides useful data for wholesale market performance. While France has much lower average emissions (50%) than the Spanish ones (due to the significant nuclear and hydraulic presence), its marginal contributions are almost double, since the last groups to enter are Fuel versus the Spanish combined cycles. Data from Figs. A.2 and A.3 in the Annex A are aggregated in Table 5, which indicates the amount of electricity generated and emissions released for each technology over the year 2016. It is striking that the main source of contamination in Spain is coal whereas it is gas for France.

Finally, the energy and emissions to manufacture and install each solar facility (1 kWp of PV) came from the Hespul [23]. This estimates that to install a 1 kWp of PV system, 2500 kWh of primary energy are needed (manufacturing process included). The point is how to convert this amount of energy into carbon emissions. The conversion depends on the place of manufacturing because, as has been seen in the previous sections, the quantity of CO_2 released for the generation of 1 kWh of electricity is very different from one country to another. Therefore, several scenarios are considered: modules can be manufactured in Spain, in France, in China or in Europe, To simplify matters, the approximation is made that all the 2500 kWh required for the fabrication process are electricity. The marginal carbon emissions for the production of electricity are 673 g CO_2/kWh and 370 g CO_2/kWh for France and Spain respectively (RTE, 2016 and REE, 2016), 530 g CO_2/kWh for Europe [48][1] and 748 g CO_2/kWh for China [17].

4. Results

4.1. Optimal size and profitability analysis

Table 6 shows that the best capacity in Spain is the 1.5 kWp one

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[1] Average value for the following countries Belgium, Czech Republic, Denmark, Finland, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, United Kingdom.

Table 5
Yearly contribution of each technology to the generation of electricity and CO_2 emissions.
Source: own elaboration with data from RTE (2016) [43] and REE (2016) [44].

	France			Spain		
	Generation (MWh)	**CO_2 Emissions Mte**	**Emission rate gCO_2/kWh**	**Generation (MWh)**	**CO_2 Emissions Mte**	**Emission rate gCO_2/kWh**
Fuel	2388,776	1.6	673	0	0	0
Gas	40,162,175	18.6	463	31,500,334	12	370
Coal	10,053,606	9.6	956	33,952,384	9.6	956
Nuclear	387,772,845	0	0	55,196,787	0	0
Hydro	67,494,269	0	0	37,305,723	0	0
Solar	7668,289	0	0	13,205,191	0	0
Wind turbines	24,630,201	0	0	51,328,525	0	0
Others	8296,612	0	983	33,450,977		
Total	**548,466,772**	**8.1**	**68**	**255,930,011**	**44**	**168**

Table 6
Financial indicators for different areas in function of the installed capacity.
Source: own elaboration

		Initial Investment (€)	Total production (kWh)	Useful energy (kWh)	Revenue (€)	NPV (€)	IRR	Pay Back (years)
Madrid	0.5 kWp	1950	772	772 (100%)	125	− 614	–	15.6
	1 kWp	2200	1545	1309 (85%)	212	1033	3.72%	10.4
	1.5 kWp	**2450**	**2315**	**1470 (63%)**	**238**	**1330**	**4.2%**	**10.3**
	2 kWp	2700	3090	1537 (50%)	249	1290	3.71%	10.8
	2.5 kWp	2950	3860	1571 (41%)	254	1113	2.02%	11.6
Seville	0.5 kWp	1950	812	812 (100%)	131	− 474	–	14.9
	1 kWp	2200	1625	1362(84%)	221	1123	4.33%	10
	1.5 kWp	**2450**	**2455**	**1507(62%)**	**244**	**1464**	**4.57%**	**10**
	2 kWp	2700	3250	1562 (48%)	253	1182	3.48%	10.7
	2.5 kWp	2950	4060	1595 (39%)	258	901	2.45%	11.4
Marseille	*0.5 kWp*	1950	752	752 (100%)	122	− 1357	–	16
	1 kWp	2200	1500	1500 (100%)	243	390	1.51%	9.1
	1.5 kWp	2450	2250	1892 (84%)	306	1190	3.74%	8
	2 kWp	**2700**	**3000**	**2057 (68%)**	**333**	**1334**	**3.82%**	**8.1**
	2.5 kWp	2950	3760	2134 (57%)	346	1261	3.33%	8.5

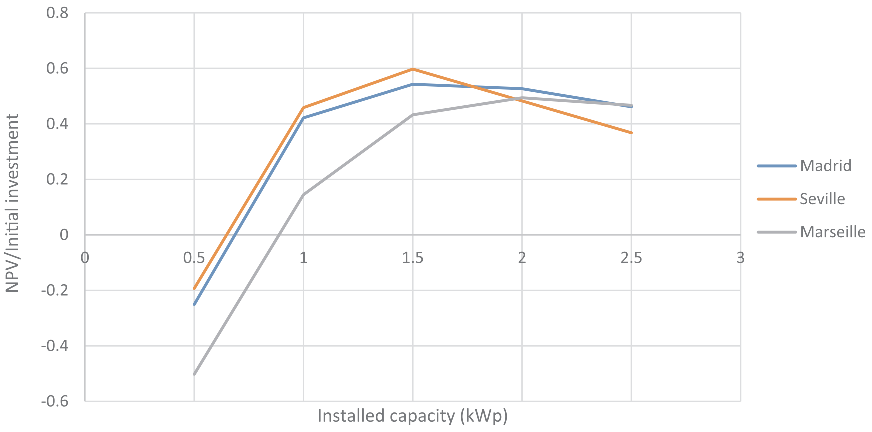

Fig. 5. Ratio NPV/initial investment for the three areas and depending on the installed capacity.
Source: own elaboration

whereas in France it is the 2 kWp one. It also indicates the corresponding investment and revenue. Fig. 5 plots the same result, the optimum capacity being the one corresponding to the top of the parabola. The profitability of the installation stays in the same range for the three areas, even though Seville gets benefits a little higher thanks to its greater irradiation. The NPV is between 1300 and 1500€ for an initial investment of 2450€ for 1.5 kWp and 2700€ for 2 kWp. The internal rate of return (IRR) is therefore between 3.8% and 4.6%. It is not a very high profitability but it is largely acceptable for an individual wishing to invest a small amount of money. The investment is recovered after 8–10 years, which corresponds to less than 50% of the system's lifetime.

The model will present better results the higher the irradiation at the selected point and the lower the emissions corresponding to the place where the PV installations have been manufactured. Any case it might be noted that when CO_2 emissions become a part of the profitability analysis many ways of pricing them exist. Among them is valuing social cost resulting from climate change (Price, 2017 [39]).

Fig. 6 represents in a tridimensional way the information provided by Table 6, where the axes x and y represent the irradiation and PV respectively, while in the z-axis the Net Present Value of each

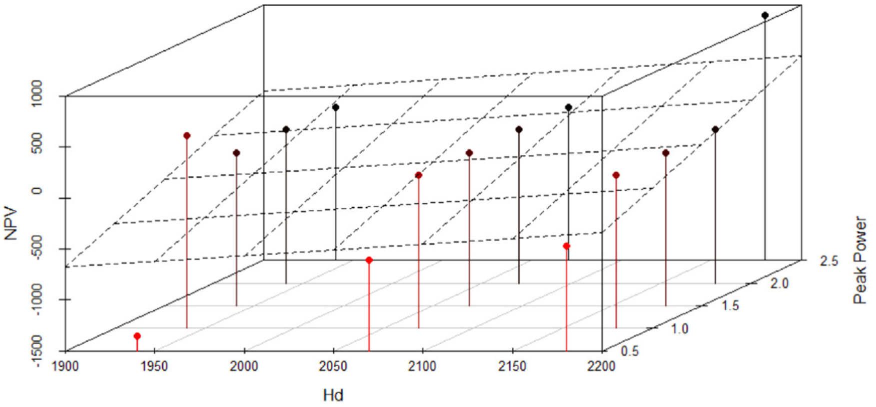

Fig. 6. Net Present Value (NPV) for each level of PV installed power and irradiation (Hd).

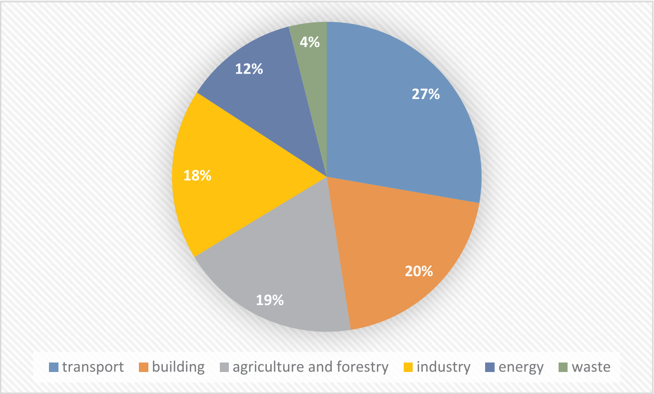

Fig. 7. Contribution of each sector to the global carbon emissions for France [33].
Source: own elaboration from Ministère de l'Écologie, du Développement durable et de l'Énergie (2016)

configuration is found. As it can be expected, the greater irradiation and installed power, the greater Net Present Value. In the same figure, it has been included an adjusted surface, based on ordinary least squares (OLS). (Fig. 7)

4.2. Energy payback time (EPBT)

As has been seen in Section 3, according to the Hespul [23], to install a 1kWp solar system, 2,500kWh of primary energy are needed (manufacturing process included). Given that the installation of a PV system is the unique moment when it needs to be supplied with energy, this data allows the calculation of the EPBT of our system in a direct way. Table 7 shows the main results.

In France, the PV system has a 2 kWp capacity, which means 5000 kWh are required for its installation. It then annually generates 2050 kWh of useful energy, therefore reimbursing its "energy debt" after only 2.5 years. The same EPBT is obtained for Southern Spain because the system has a smaller installed capacity but proportionally provides the same amount of useful energy. For the Center and the North of Spain where the irradiation is a little bit lower, the EPBT is slightly higher.

Table 7
EPBT of the system in function of the geographic area.
Source: own elaboration

Location	Useful Energy **(kWh/year)**	Energy necessary to the installation **(kWh/year)**	EPBT **(year)**
Seville area (1.5 kWp)	1510	3750	2.5
Madrid area (1.5 kWp)	1470	3750	2.55
Marseille area (2 kWp)	2050	5000	2.5

In any case, the EPBT represents approximately 10% of the installation's lifetime, which is a satisfactory value considering that the model studied in this paper has used a very conservative hypothesis. By comparison, Tremeac and Meunier [53] found an EPBT of 1.7 years for their 4.5 W wind turbine installed in France and designed to run during 20 years. Guezuraga et al. [19] estimated it at 0.6 years for a 1.8 MW capacity located in Austria and Uddin and Kumara [54] between 1 and 3 months for installations in Thailand.

4.3. Carbon emissions per kWh

Thanks to the data detailed in Section 3, the emission balance of CO_2 derived from the installation of a PV system can now be calculated. In France, newly installed solar energy substitutes the fossil fuel-based electricity. In these conditions, a 2 kWp installation, which is the optimum according to the previous section and which annually produces 2050 kWh of electricity, can avoid the release of 1384 kg of CO_2 into the atmosphere each year. In Spain, this amount is a little lower (558 kg/year) since the solar energy compensates the generation from gas combined cycle plants and since the optimum capacity to maximize the profitability is only 1.5 kWp. In the last section of this paper, these quantities will be generalized at a national level and compared to the reduction objectives established by the Paris Agreement.

Table 8 displays the main results for each scenario and highlights two important findings: the emissions avoided and the carbon emissions balance. The later derives from comparing the carbon emissions avoided and generated expressed in kg CO_2. It is worth mentioning that the emissions relative to the transport between the places of manufacturing and installation are not taken into account in the balance because they are really low in comparison with the other sources of emissions. The results show that in every scenario the emission balance is negative; that is to say, that the production process generates less CO_2 emissions than the system will save during its whole life. It means the PV system has always a positive impact on the environment. In the best case (fabrication and installation in France), the quantity of CO_2 saved is 100 times higher than the quantity generated. Unfortunately, this situation may not be totally representative of the reality because the majority of the modules installed in France are not manufactured there.

From carbon released during the manufacturing process in Table 8, the CO_2 emissions assigned by kWh can be easily calculated by dividing this amount by the total production of the system over its lifetime [20,3]. Results for the different scenarios are displayed in Table 9. The values obtained are around 8–83 g CO_2/kWh. This is a wide range that illustrates the importance of taking into account both places of

Table 8
Emissions balance considering place of fabrication and installation, taking into account only useful energy.
Source: own elaboration

Place of manufacturing	China		Europe		Spain	France
Place of installation	**Spain**	**France**	**Spain**	**France**	**Spain**	**France**
Emissions avoided (kg of CO_2)	− 13,900	− 34,600	− 13,900	− 34,600	− 13,900	− 34,600
Emissions generated by the manufacturing process (kg of CO_2)	2850	3740	1988	2650	626	340
Emission Balance (kg of CO_2)	**− 11,050**	**− 30,860**	**− 11,912**	**− 31,950**	**− 13,174**	**− 34,250**

Table 9
Carbon emissions assigned by kWh for different location scenarios.
Source: own elaboration and [8].

Place of fabrication	China		Europe	Spain		France
Place of installation	**Spain**	**France**	**Spain**	**France**	**Spain**	**France**
Carbon emissions (g CO_2/kWh)	83.1	83.3	58.9	58.10	18.6	7.6

Table 10
Carbon emissions from LCA of different RES (g CO_2/kWh).
Source: own elaboration

	Hydro-Power energy	Wind turbines	Photovoltaic Energy
Pehnt [37]	(10–13)	(9–11)	104
Jacobson [28]	(17–22)	(2.8–7.4)	(19–59)
Evans et al., [13]	41	25	90
Mulvaney [35]	12	5	35

fabrication and installation when it comes to making the LCA of a PV system.

5. Discussion

5.1. Analysis of PV carbon emissions

The total carbon emissions per kWh assigned to PV for the different scenarios calculated shows values ranging from 7 to 83 g CO_2/kWh. Our results are coherent with those quoted in the literature review, which were between 12 and 68 g CO_2/kWh ([35,49] and the Parliamentary Office of Science and Technology UK, 2006). Nevertheless, obtaining such a wide range of values for a unique indicator can be a little unsatisfying. Indeed, promoting a green energy saying it releases only 10 g of carbon for each kWh generated is quite different from saying it produces 8 times more emissions. This is why additional research is needed on the meanings of the results established in the previous section.

The first thing to note is that the manufacturing place influences much more the environmental impact that the PV system will have than its final location. Indeed, even if only France and Spain are here considered as places of installation, they are two countries with different solar irradiation and, above all, with distinct electricity generation systems, but the results for both cases are almost the same (see the second and third columns of Table 8).

The lowest value (7 g CO_2/kWh) is obtained considering that all the energy required for the manufacturing process of the solar modules is electricity and that this process takes place in France. Unfortunately, this theoretical result may not be very representative of the reality for several reasons. On the one hand, very few PV systems running in Europe have been manufactured there. Though official data do not exist, it is estimated that a very large part of them is imported from China, where the contamination and the carbon emissions are much higher. On the other hand, the hypothesis regarding the energy necessary being only electricity is quite optimistic. This could happen in an optimized production system but it is not the case in the majority of them. Consequently, total assigned emissions of 7 g CO_2/kWh for solar energy is theoretically possible but the PV systems that are commonly used cannot reach such a low rate of emissions.

Then, if our results are not as favorable as the literature generally says, it is because our model is conservative (due to the absence of energy storage, to the fact that no electricity is sold back to the grid and that only the useful energy is considered). But it means that these values (80 and 60 g CO_2/kWh, respectively) are representative of a certain reality and could, for instance, be used in a pessimistic scenario for the evaluation of emissions in a larger context.

It is interesting to compare the assigned carbon emissions of LCA for a PV system with RES technologies. The comparison is here limited to the wind-power and the hydraulic energies, which are often considered as the direct competitors of PV. The comparison with the nuclear option would not be relevant since too many other factors would have to be integrated (storage of the nuclear waste, risks of explosions, ethical issues, and so forth).

Table 10 displays the data of four authors who have carried out comparative works on carbon emissions assigned to RES. Two relevant points can be noticed. The first is that in every case, PV energy has higher assigned carbon emissions than the other two sources. The second is that here again the values proposed vary depending on the paper. This illustrates the complexity of dealing with LCA, the large number of factors involved and the numerous ways of calculation existing both leading to a wide range of results. Nevertheless, determining the carbon emissions from LCA of an energy source remains a great way of measuring its impact on the environment and is an excellent tool to evaluate the emissions at a national or international level. Therefore, it can be very helpful for planning and reaching carbon-reduction objectives.

These results will improve in the next few years, due the expected reduction in the PV cost. The forecast of the costs of photovoltaic installations planned by the scientific community for the coming years are reductions above 50% and, therefore, the carbon emissions from LCA [51].

5.2. Contribution to meet the Paris Agreement's commitments

As was explained in the presentation of the model, one PV system installed in France helps to reduce the emissions relative to the fuel-based generation of electricity. But, if many PV systems are mounted we could hope to cancel all the emissions corresponding to the utilization of fuel and also the emissions due to the following technologies entering into the electricity generation. In France, the next two technologies to enter are gas and coal, and the rest of the electricity demand is fulfilled with zero emission sources (nuclear and RES). Consequently, the maximum amount of electricity which is produced by carbon emitting sources is approximately 9000 MW (value reach during peak hours in winter), of which 300 MW correspond to fuel, 1800 MW to coal and 6900 MW to gas. To fulfill this demand with only a 2 kWp domestic solar system, it would be necessary to equip 4.5 million houses. Given that there are 27 million dwellings in the country and that 40% of them correspond to houses and not apartments[2] this is something that is feasible. Besides, installing PV systems in more than 4.5 million homes would not be interesting in terms of carbon emission considerations. Indeed, this investment is enough to compensate all the carbon-emitting technology in the generation of electricity, and if more solar modules were mounted they would substitute nuclear or hydraulic generation, which already are zero emission energies (only carbon emissions are taken into account here).

In this case, 150,000 systems would be installed to compensate the fuel utilization, annually avoiding the release of 0.207 Mt CO_2. Additionally, 3.45 million would stand for the compensation of gas, corresponding to a 3.28 Mt CO_2 reduction, and 900,000 for the coal, reducing 1.76 Mt CO_2 more the emissions. In total, 5.24 Mt CO_2 would not be released into the atmosphere each year (see Table 11). This amount represents 1.67% of the 1990 level of emissions and would help to reach the French abatement commitment which implies to emit only 40% of 1990 emissions up to 2030. The reduction objectives could, therefore, be reached only with these new installations during the first five years of the project. Furthermore, the total amount of the investment would be worth billion EUR 12.2.

Finally, in its low carbon strategy, the government contemplates increasing the taxes on fossil energies more and more in order to encourage investment in renewable ones. This is evidence that a massive investment in solar energy would be profitable for both the economy and the environment.

Spain has the same reduction commitment as France but has not yet published its long-term reduction strategy [1]- We will hence compare the reduction obtained thanks to the PV system to the global reduction objective. The country has a share of carbon-emitting sources of energy much higher than France, the coal and the combined cycle accounting for approximately 7000 MW and 8000 MW during peak hours. As a result, 10 million homes equipped with 1.5 kWp PV systems could replace these two contaminating technologies. As Spain contains 25 millions of households of which 40% are houses as well, it would mean taking advantage of the maximum domestic capacity of the territory for solar energy. This investment would allow compensating for the 6.45 Mt CO_2 emitted by the coal activity and 3.07 Mt CO_2 relative to the combined cycle (their respective rates of emissions are 950 and 370 g CO_2/kWh). In total, 9.52 Mt CO_2 would be saved each year (see Table 11). This amount represents 4.7% of the 1990 level of emissions and would help to reach the Spanish abatement commitment which implies to emit only 40% of 1990 emissions up to 2030. Moreover, this project would require an initial investment of billion EUR 24.5 and, thanks to its profitability, it would generate an annual revenue that could be re-injected into the market.

6. Conclusions

This paper has explored the viability of residential PV systems, taking advantage of the information coming from the smart meters that are currently being installed in Europe. This large amount of information, along with the significant cost reduction of PV facilities, have made it possible to determine the optimum capacity for each client, presenting positive results from an economic point of view. On the other hand, this kind of small power plants has an important contribution to emission reductions. The paper addressed two main objectives:

1. The development of an algorithm that, using the hourly load curves of smart meters from the points of supply and the marginal costs of the electricity for the residential customer, determines the optimal size of the plant and its associated profitability.
2. The estimation of the savings of emissions that the installation of each of these plants would have, as well as the impact that the massive installation of these facilities would have on the fulfillment of the commitments of each country to the Paris Agreement.

The main results of this paper are that, with the current level of cost of the PV systems and electricity, the PV residential facilities are profitable in all the locations analyzed (Seville, Madrid and Marseille). As we might expect, the more irradiation and higher the price of electricity, the greater the profitability of the installations (therefore Seville is the most profitable). The solar power that the model proposes to install is approximately one-third of that contracted (for a standard consumer), and it is noteworthy that close to 40% of the energy produced is not used, the model proposing an overcapacity operation, at least during the central hours of the day. As this document provides a general methodology, this value could be estimated for any user and for any location.

Although they may seem small returns to be attractive, the reductions in investment costs expected by the scientific community for the coming years, coupled with the maintenance of electricity prices, will make the profitability of this type of facility increase significantly.

To analyze the environmental impact, the equilibrium in the hourly generation market is considered, calculating the reduction due to the emissions of the energy displaced. The emissions produced due to the energy consumption for its manufacture are calculated using the average values of each possible producing country. The results show that, regardless of the place of manufacture and installation, these devices make a positive and important environmental contribution. It is worth noting the significant environmental contribution that these facilities represent in France (at least for the first installations), since the energy they displace comes from fuel oil plants (673 g CO_2/ kWh), despite the low average emissions for this country (thanks to the significant share of nuclear and hydraulic in its energy mix).

Finally, an estimate is made for the possible contribution of these facilities to the INDC of the Paris Agreement[3] (COP-21). The comparison of the contribution of individual emissions with the total number of electricity industry emissions by technology in each country leads us to estimate for France 4.5 million customers as the maximum compatible with no clean generation technologies, the first 150,000 customers being extremely efficient, offsetting fuel emissions. In the Spanish case, it could be installed for the totality of the house customers (not flats, 10 million in total). The total emission reduction is close to 5 and 10 $MtCO_2$ per year for France and Spain respectively, which are an important part of their national commitments. To reach these levels, it is necessary to make a profitable investment of 12 and 25 billion €.

Finally, and as a consequence of this work, we can propose some recommendations to the Regulator, to enable developing this in an orderly way. The installation of residential solar seems to be a very efficient way to reduce the levels of emissions, which is a reason why the Administration should serve as a catalyst and facilitator of this deployment.

1. To this end, and given that the investment could be an entrance barrier for individuals, the Administration:

- Should favor agreements with the contractors in order to ensure a fixed price for each type and installation (or at least the maximum), avoiding contractor abuse.
- Should create a purchase center, since the massive acquisition of panels and inverters capturing the economy of scale, can significantly reduce the investment, ensuring, at the same time, the quality of equipment.

2. Another important point concerns the administrative procedures. In

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[2] Institut National de la Statistique et des Etudes Economiques (2016) [26].

[3] An analysis of the possible measures to be taken is in Arcos (2017).

Table 11
Investment required at a national level to substitute the carbon-emitting technologies in the generation of electricity.
Source: own elaboration

	Total houses **equipped**	Technology **substituted**	Corresponding **houses**	Emissions compensated **($MtCO_2$)**	Emissions avoided **($MtCO_2$)**	Price per installation **(€)**	Total Investment **(billion €)**
France	4.5 million	fuel	150,000	0.21	5.24	2700	12.2
		gas	3450,000	3,28			
		coal	900,000	1,76			
Spain	10 million	gas	5400,000	3.07	9.52	2450	24.5
		coal	4600,000	6.45			

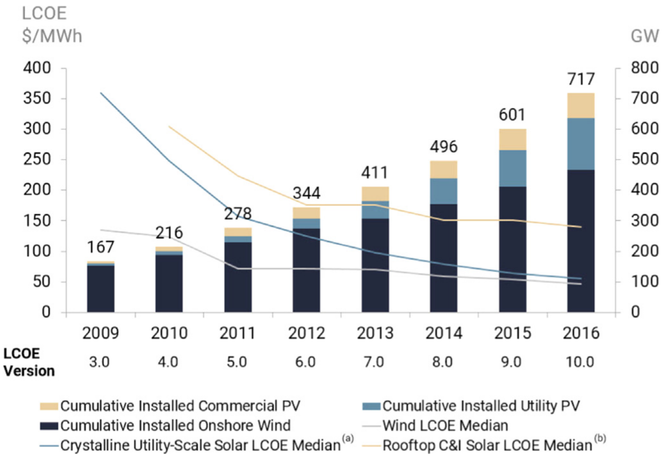

Fig. A.1. Growth of the PV sector and decline of the costs between 2009 and 2016.
Source: Lazard [30]

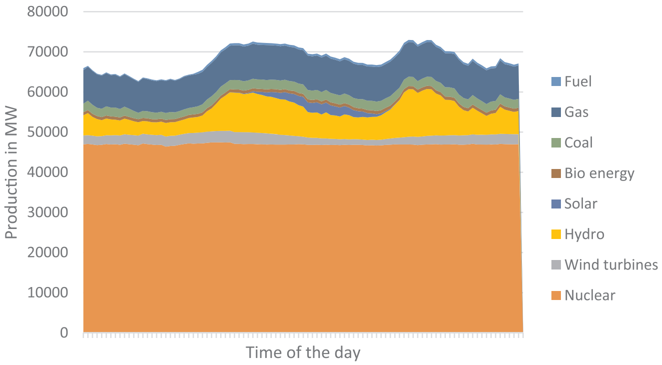

Fig. A.2. Contribution of each technology for the French global production of electricity on December 14th, 2016 [44].
Source: RTE (2016) and own elaboration.

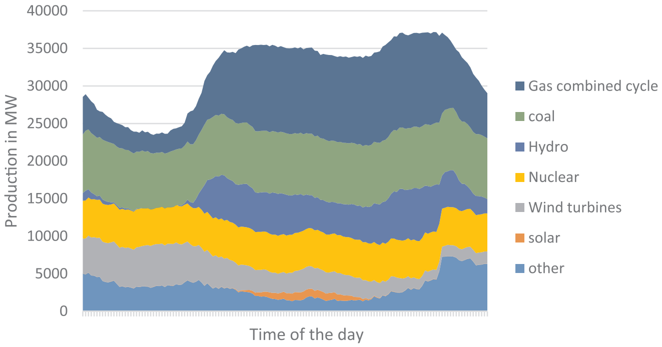

Fig. A.3. Contribution of each technology for the Spanish global production of electricity on December 14th, 2016.
Source: REE (2016) and own elaboration.

order to minimize them, the Administration:

   - Should eliminate all taxes and fees to the construction and commissioning of this kind of facilities.
   - Given that the design proposed does not realize any sale of energy and it is a mature and safe technology, all prior authorization should be eliminated, and all the verification done by the contractor, informing the Administration *a posteriori*.

3. The existence of service companies that could carry out the supervision, maintenance and reviews of the plants, would give the client a high level of confidence. These companies could make the investment by recovering these amounts of energy savings over a period of time (ESCO scheme). Crowd funding initiatives could be a perfect way to fund the project.
4. Although the rate of interest is at a historical low, the provision of credit lines without interest or guarantees would foster its development, with practically no cost for the Administration

Further research can be carried out in this field. For instance, by expanding the analysis to consider a Time of Use (TOU) Tariff, considering the actual avoidance cost of each hour instead of working with a fixed price and the introduction of storage for using all the energy produced.

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Annex A

See Annex Figs A1–A3

Figs. A.2 and A.3 present, for France and Spain on December 14th, 2016, the distribution of the different technologies contributing to the generation of electricity. The technologies situated at the top of the curve are the carbon-emitting ones and are ordered in function of their entrance ranking (the most expensive technology is the last to enter the production system). Fig. A.2 reveals that around 70% of the French electricity is produced from nuclear energy and that the marginal emissions correspond to the utilization of fossil fuel. Fig. A.3 shows that in Spain the distribution between all the technologies is much more homogeneous, which implies that the presence of carbon-emitting ones is higher. The marginal emissions are in this case relative to the gas combined-cycle, which generates an important part of the national electricity, especially during peak hours.

This information is available hour by hour from RTE and REE for France and Spain, respectively.

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