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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.