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Combining feed-in tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: Comparative economic assessment and policy implications for European countries

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Abstract

In the last fifteen years, Europe has been involved in the major development of photovoltaic (PV) solar energy. The Kyoto Protocol requirements and the European Union (EU) directives to promote the use of renewable energy sources (RES) together with environmental policies introduced for the development and use of alternative energies have generated a large number of market opportunities for this sector. Differences in the application of energy policies have caused significant imbalances in electricity systems and distortion of electricity prices. The main concern of governments is to define the support schemes to be used and how to combine them in the most profitable manner. The aim of this paper is to provide a comparative cost-effectiveness assessment using feed-in tariffs (FiT) and net-metering (NM) schemes in some representative EU countries. The authors have developed an economic model to evaluate the profitability of PV projects combining these support schemes. Results show not only the circumstances under which solar energy is economically profitable, but also the kind of

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PV systems, locations, minimum levels of tariff prices and specific combination of support schemes that should be promoted.
Keywords: Photovoltaic energy, Feed-in Tariff, Net-metering, Profitability, Scheme combination

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1. Introduction

Energy is the basis of the economic development of society and the sun is the largest source of energy that exists, as well as being a virtually inexhaustible source. In 2014, energy consumption was equal to 1777 Mtoe (Million tonnes of oil equivalent) in Europe (Enerdata, 2012; IEA, 2015a) while at global level it was around 13737 Mtoe, 0.5% more than in 2013. This energy accounts for only 0.05% of the free solar energy that the earth receives, which comes with zero CO_2 emissions (Hosenuzzaman et al., 2015; Sahu, 2015).

Although the ratio of renewable energy (RE) use is still low by comparison to conventional energy, it is continually growing. In 2014, 58.5% of new installations worldwide used RES (EPIA, 2015). Electricity consumption in 2014 was 3226 TWh in Europe (Enerdata, 2012). Of this, 32.7% was covered by RES. PV energy contributes around 1.3% of the global electricity demand, 3.5% of the electricity demand in Europe (IEA, 2016b). Furthermore, Europe represents around 42.3% of the worldwide installed capacity (EPIA, 2015; IEA, 2016b).

Energy consumption is one of the most serious concerns of governments around the world, especially in EU countries (European Parliament, 2009, 2012). The increasing impacts of the use of conventional unclean energy sources on global warming requires the identification of policies to limit the unrelenting degradation of the planet (IEA, 2015d; IPCC, 2007). The Kyoto Protocol agreements (U.N., 1998) define policies to enhance energy efficiency, and also to promote the use of sustainable energy sources. Additionally, measures to reduce CO_2 emissions in different countries have been applied, and the use of penalties if these goals are not met has been implemented.

In 2015, a new record for installed solar power was reached in Europe, with the addition of 8.5 GW, representing a total installed capacity of 97.14 GW. Germany, Italy, the United Kingdom, France, Spain, Belgium and Greece have 85.7% of the total installed capacity in Europe. The share of RE is expected to increase in the future. EU authorities have decided to define new clean energy targets for 2030, when the contribution of RES to the total energy mix will be at least 27%.

Within this framework, solar power is beginning to play an important role in power generation in many countries. However, the application of policies to promote the use of PV energy has caused significant imbalances in electricity systems and distortion of electricity prices. A well-planned policy is needed to control its impact on the electricity market and the development of PV energy must be well-controlled (Avril et al., 2012; Pyrgou et al., 2016). Thus, the main concern of governments is to define the energy support schemes to be used and how to combine them in the most profitable manner for a better-balanced electrical power generation system.

In the recent literature, some authors have focused on the economic analysis of the main support policies for solar PV. Pyrgou et al. (2016) examined the FiT scheme in-depth to evaluate its sustainability, feasibility conditions and effect on electricity prices. Dusonchet and Telaretti (2010a,b, 2015) and Campoccia et al. (2014) used economic indices to compare support policies and define the best profitability conditions in the different countries analysed. Mir-Artigues and del Río (2014) presented a cost-effectiveness analysis to test whether a combination of a primary instrument (FiTs) with secondary instruments (investment subsidies and soft loans) led to lower support costs compared to the use of FiTs alone. Some authors studied the financial benefits and performance of the main mechanisms in different countries (Avril et al., 2012), while, with a more global vision, others analysed solar energy technologies, prospects, progress and policies in relation to other energy sources (Hadjipanayi et al., 2016; Hosenuzzaman et al., 2015). Nevertheless, as yet, no research has been conducted on the potential combination of FiT and NM schemes. Furthermore, most publications have evaluated the results of applied policies, showing the success or failures in their implementation, but not with a view to presenting the most suitable mix of these schemes to improve future PV development.

The present paper presents a model to evaluate the profitability of PV systems with different combinations of FiT and NM support schemes. The paper makes three contributions to the literature on the topic of PV support schemes assisted by an economic model. The first and main contribution is to evaluate which combinations of FiTs and NM might be appropriate for a certain country and to define the ranges of FiT prices that best combine with NM policies as a function of the electricity prices to create a profitable development. The second contribution is to provide a comparative assessment between the seven EU countries that have experienced the fastest PV development in recent years, with the goal of helping identify their potential future PV development. The third contribution is to highlight the conditions for making efficient decisions concerning where, how and upon which requirements PV policies must be promoted.

The rest of the paper is structured as follows: Section 2 analyses the evolution of PV development in the European context with regard to both installed capacity and satisfied electricity demand covered. Section 3 focuses on the legal aspects, specifying the policies that have been implemented in the main EU countries. Section 4 defines the economic model and the main parameters to be considered in an economic analysis of PV systems. Section 5 presents comparative economic results for the selected PV systems in seven representative EU countries. Section 6 summarises the main conclusions and recommendations of the authors regarding PV energy policy.

2. PV energy in the European context

The PV market in Europe has grown rapidly over the past fifteen years. The total installed and accumulated PV electric power in 2015 reached 97.14 GW, representing a growth factor of 750 since 2000 (0.129 GW installed in 2000 to 97.14 GW installed in 2015). Figure 1 shows the cumulative installed capacity in Europe by country during the last fifteen years, in percentage (IEA, 2016a,b;

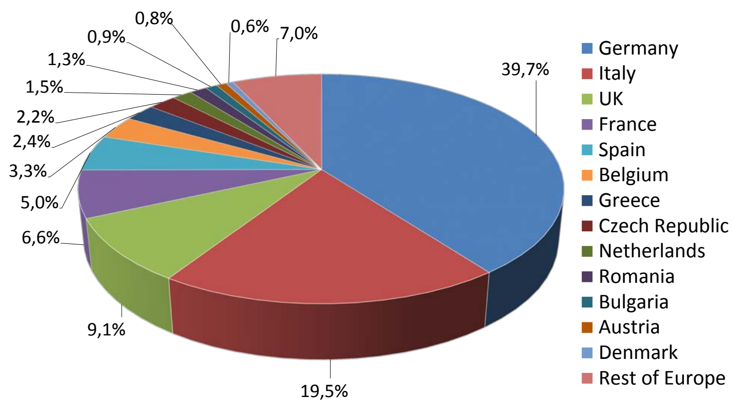

Figure 1: European solar PV cumulative installed capacity 2000-2015 (in percentage by country).

REN21, 2015a,b).

Regarding the rate of electricity demand covered by different energy sources, currently countries such as Italy, Greece and Germany have enough PV capacity to cover 8%, 7.4% and 7.1% of their annual electricity demand, respectively. More than twenty countries in Europe have enough PV capacity to produce at least 1% of their electricity demand from PV, which represents at least 3.5% of the electricity demand and the 7% of the peak electricity demand. In addition, 75% of the total PV installed capacity in the world from 2002 to 2011 was located in Europe (IEA, 2016b).

Germany, Italy, the United Kingdom, France, Spain, Belgium and Greece have led photovoltaic development in Europe over the last 15 years. These seven countries have installed 85.7% of the total PV capacity installed in the EU. The other countries represent 14.3% of the total PV market (mainly Czech Republic, Netherlands, Romania, Bulgaria, Austria and Denmark). Figure 2 shows the evolution of the annual PV installed capacity in the seven selected countries. It can seen that, except for the United Kingdom, the other countries have experienced a similar pattern of behaviour in relation to the annual installed capacity, with a period of rapid growth –maintained for two or three years– followed by

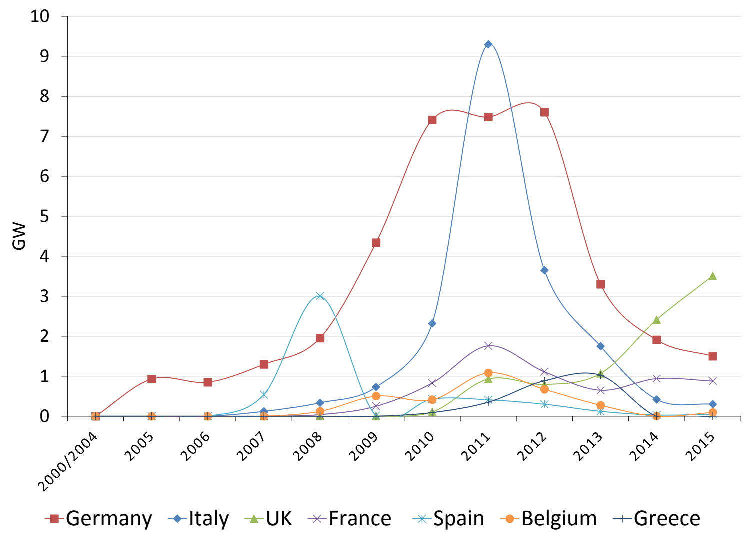

Figure 2: Annual installed PV capacity by country, in GW.

a sharp decrease.

The development of PV in Europe emerged in 2000, but it was not until 2005 that policy decisions resulted in substantial installed capacity, first in Germany, followed by other countries. In 2007 and 2008, significant growth was achieved due to photovoltaic development in Spain. Total installed capacity reached 4 GW by 2008 despite the Spanish government having set a goal of just 500 kW. Thereafter, support policies were significantly discouraged and the Spanish PV market decreased in 2009. The special case of Spain shows the effects of unplanned policies and suggests PV development should be more carefully implemented.

Since 2009, Germany has marked the highest growth rate in installed capacity. In retrospect, it may be seen as a consequence of the first phase of the financial crisis, but also as a year of stabilization after the PV boom of 2008. Major growth returned in 2010, achieving unprecedented installation figures with 7.29 GW in this country, and Italy and France together adding a capacity of around 3.3 GW.

In 2011, the PV market reached the maximum installed capacity with 17.7 GW in total. Italy installed 9.3 GW in new systems, followed by Germany with 7.53 GW and France with 1.76 GW. In the case of France, this new capacity was largely due to the connection of projects installed in 2010.

The PV market suffered a significant downturn from 2013, affecting the largest EU countries. Annual installed capacity was 10.66 MW in 2013 and 7.03 MW in 2014. However, in 2015 the market showed signs of economic growth again, with 8.5 GW of new installed capacity, mainly through the development of the British market, with 3.51 GW, followed by 1.5 GW installed in Germany and around 0.9 GW in France.

3. Support policies in the EU countries

Different policies have been implemented in the EU countries in order to stimulate the installation of RES power plants and satisfy the legislative measures promoted by the EU. This is commonly known as the Renewable Energy Directive that imposes on all EU countries a renewable energy share of 20% in the energy mix, 20% reduction of greenhouse gases and 20% energy efficiency in 2020, with different targets for the member states. In 2014, a new directive defined new targets through to 2030 but this is not yet compulsory.

The main support policies implemented in the principal EU countries in the recent years are the following:

- Feed-in-tariff (FiT). The producer receives total payments per kWh of generated electricity with a fixed price. It is guaranteed by the government.

- Feed-in Premium (FiP). The producer receives a payment per kWh on top of the electricity wholesale-market price. It is also guaranteed by the government.

- Investment subsidies. Based on a percentage of the renewable energy output or the specific investment upfront cost.

- Tax reductions. Exemptions on taxes, tax refunds, lower VAT rates or advantageous amortization schemes.

- Soft loans. Provided by the government with a rate below the market interest rate.

- Tradable Green Certificates. Certificates that can be sold in the market, allowing RES generators to obtain revenue, in addition to the earnings from the sale of electricity fed into the grid.

- R&D incentives: R&D subsidies and demonstration programs.

- Call for Tenders. The government invites RES generators to compete for either a certain financial budget or a certain RES generation capacity.

- Net-metering (NM) and self-consumption (SC) schemes. Billing agreement between utilities and their customers to feed electricity the producer do not use back into the grid.

Table 1 summarises the main financial support schemes implemented in the seven EU countries in recent years, which are analysed in the present work. Some authors such as Mir-Artigues and del Río (2014), Campoccia et al. (2014), Dusonchet and Telaretti (2015), Sahu (2015), Dufo-López and Bernal-Agustin (2015) and Pyrgou et al. (2016) have studied in detail these different support policies and their combinations. All of them agree that combinations of FIT and FIP with either investment subsidies or soft loans have been the most common financial support scheme in most EU countries and the basis of the PV development in recent last years. However, unfortunately, also this has also been the origin of the main imbalance in the electrical power systems and the distortion of electricity prices. Furthermore, authors agree that NM as a support scheme must be launched in most of the countries to enable grid-connected prosumers to offset their electric consumption and received payment for the excess energy they are injecting in the grid.

Table 1: Support Schemes in the EU selected countries

Support Scheme	Country					
	Germany	Italy	UK	France	Spain	Belgium	Greece
Feed-in tariff/Feed-in premium	Active, 20 years, "Corridor" concept	Used but cancelled in 2013 for plants over 20 kW	Active, 20 years, "Corridor" concept	Active for systems up to 100 kW	Used but cancelled in 2013	Used but cancelled in 2014	Active
Investment subsidies	Active	Active at regional level	Not used	Active at regional level	Active	Active at regional level	Not used
Tax reductions	Not used	Active	Not used	Used but cancelled in 2014	Active	Active at regional level	Not used
Loans	Active	Active	Active	Not used	Not used	Active at regional level	Not used
Green Certificates	Active	Not used	Active, linked to ROC	Not used	Not used	Active with quota obligation	Not used
R&D incentives	Active	Active	Active	Active	Active	Not used	Not used
Call for tender	Not used	Not used	Not used	Used	Used	Not used	Not used
Net-metering	Active	Active. Up to 500 kW from 2015	Active in combination with FiT	Active	Planned but not used	Active	Active from 2013 up to 20 kWp
Current legal framework	Act of Granting Priority to Renewable Energy Source (EEG) (Gesetz für den Vorrang Erneuerbarer Energien, 2011)	Decree of the 5th of July 2012 (Ministero dello Sviluppo Economico, 2012) and SC regulation (AAEG 74/2008 and AEEG 570/2012/R/efr)	The Feed-in Tariffs Order 2012 (Department of Energy and Climate Change of the UK, 2012)	Decree no. 2000-1196 (Minister de l'économie des finances et de l'industrie, 2000) updated in July 2016 (Minister de l'économie des finances et de L'industrie, 2016)	Royal Decree 413/2014 (Ministerio de Industria Comercio y Turismo, 2014) and Royal Decree 900/2015 (Ministerio de Industria Energía y Turismo, 2015)	Several governmental policies (Huijben et al., 2016)	Decree 4001/2011 (Hellenic Republic, Ministry of Development, Directorate General for Energy, 2011)

4. Economic and Competitiveness Analysis

The authors of this paper have developed a model to evaluate the profitability of a PV power plant with different support schemes combinations and under a wide range of scenarios. The model performs the economic analysis using the main drivers determining the profitability of the investments: legal (support schemes and energy policy), economical (price of electricity, inflation), financial (cost of capital), technological (PV system, PV module, efficiency, tracking system), related to the location (solar irradiation), maintenance and repair costs, insurance and others.

Based on the methodology designed, the theoretical framework with the equations associated with the economic model will be described first, while the different PV systems definition and input variables required by the model are explained in the following subsections.

4.1. Theoretical framework

The economic model computes the most significant variables regarding the profitability analysis of a PV project: Cash Flow (CF), Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PBP). Some authors have used these variables in other works (Chen et al., 2012; Hasanuzzaman et al., 2011; Kumar, 2015; Smestad, 2008). In addition, the authors include in this model the concept of FiT minimum, which means the minimum FiT purchase price from which the project begins to be profitable. The economic analysis also refers to the combination of FiT and NM supporting schemes.

4.1.1. Cash flow

The cash flow, CF_t, is calculated for each time period t (a year in our study) by means of Eq. (1):

$$CF_t = \sum_{t=1}^{n} I_{i,t} - \sum_{t=1}^{n} E_{i,t} \tag{1}$$

where:

- $I_{i,t}$ is the sum of the total incomes in the t period (monetary units)
- $E_{i,t}$ is the sum of the total expenditures in the t period (monetary units).

The incomes gross receipts are calculated by means of the following equation, Eq. (2):

$$\begin{aligned} I_{i,t} &= I_{1,t}\, e_{1,t} + I_{2,t}\, e_{2,t} = \\ &= P_{1,t}\, \beta_i\, \eta_s\, [1-(t-1)\gamma_m]\, e_{1,t} + \\ &+ P_{2,t}\, \beta_i\, \eta_s\, [1-(t-1)\gamma_m]\, e_{2,t} = \\ &= \beta_i\, \eta_s\, [1-(t-1)\gamma_m]\, \big(P_{1,t}\;\, e_{1,t} + P_{2,t}\, e_{2,t}\big) \end{aligned} \tag{2}$$

where:

- $P_{1,t}$ is the total power of the installation that is granted by the FiT incentive (kW).
- β_i is the solar irradiation in the plant location (kWh/m2).
- η_s is the efficiency of the PV system, also known as performance ratio.
- γ_m is the coefficient that represents the depreciation of the PV module along its life cycle.
- $e_{1,t}$ is the price of the PV energy the producer receives as FiT incentive (€/kWh).
- $P_{2,t}$ is the total power of the installation (kW) used for self-consumption (SC) and subject to the NM scheme.
- $e_{2,t}$ is the electricity market price (€/kWh).

The expenses are calculated by means of the following Eq. (3):

$$E_{i,t} = C_{om,t} \ + \ C_{ins,t} \tag{3}$$

where:

- $C_{om,t}$ is the annual cost of maintenance, repair and operating supplies. It is a percentage of the initial investment (upfront costs) of the project.

- C_{ins} is the insurance cost of the PV installation, and calculated as a percentage of the current installation value.

Once the cash flow for each period is calculated by Eq. (1), the profitability of the project is evaluated by means of the Net Present Value (NPV), the FiT minimum, the Internal Rate of Return (IRR) and the Pay-back Period (PBP).

4.1.2. Net Present Value

The NPV represents an estimation of the future cash flows referenced to the present moment and considers the Weighted Average Cost of Capital (WACC) imposed on the project. Therefore, NPV determines the present value of an investment by the discounted sum of all cash flows received from the project. Smestad (2008) and other authors have used Eq. (4) in previous works, where S stands for the initial investment.

$$\begin{aligned} NPV &= -S + \sum_{n=1}^{t} \frac{CF_n}{(1+WACC)^n} = \\ &= -S + \frac{CF_1}{(1+WACC)^1} + \frac{CF_2}{(1+WACC)^2} + ...+ \\ &+ \frac{CF_n}{(1+WACC)^n} \end{aligned} \quad (4)$$

4.1.3. FiT minimum

The concept of FiT minimum is included here by the authors in order to determine the minimum FiT price that makes the investment profitable. It is the FiT value at which the NPV of all the project cash flows (both positive and negative) is equal to zero. The minimum FiT price is calculated by means of the expression that reduces the NPV to zero, as represented in Eq. (5)

$$NPV = -S + \sum_{n=1}^{t} \frac{\beta_i \, \eta_s \, [1-(t-1)\gamma_m] \left(P_{1,t} \; e_1 + P_{2,t} \, e_2\right)}{(1+WACC)^n} - \\ - \sum_{n=1}^{t} \frac{C_{om,t} \; + \; C_{ins,t}}{(1+WACC)^n} = 0 \qquad (5)$$

where e_1 in the Eq. (5) is the value that corresponds with the FiT minimum.

4.1.4. Internal Rate of Return

The Internal Rate of Return (IRR) is the interest rate at which the net present value of all the cash flows (both positive and negative) from a project or investment are equal to zero. The IRR is used to evaluate the attractiveness of a project or investment. If the IRR of a new project exceeds a company's required rate of return, i.e. the WACC, the project is desirable. If the IRR falls below the required rate of return, the project should be rejected. Using the expression of the NPV, the discount rate IRR is calculated by the expression that reduces the NPV to zero, as represented in Eq. (6).

$$NPV \; = -S + \sum_{n=1}^{t} \frac{CF_n}{(1+IRR)^n} = 0 \qquad (6)$$

4.1.5. Pay-back

The project Payback Period (PBP) shows the time (number of years) required to return the total investment. It is calculated from the cash flows results once the NPV in the year in question is equal to zero. In the evaluation of the PBP, some authors such as Hosenuzzaman et al. (2015), Dusonchet and Telaretti (2015), Campoccia et al. (2014) and Smestad (2008) determine the PBP from the yearly CF without considering the effect of the WACC. The present work considers the time effect and the effect of the WACC in order to calculate the PBP from the yearly net present value.

4.2. Operative hypotheses

Several operative hypotheses have been assumed in the work in order to evaluate the profitability parameters in the seven selected EU countries. First at all, five types of support schemes with a combination of FiT and NM have been considered:

- Scheme combination 100/0. This implies 100% of the PV generated energy is fed into the grid and remunerated by means of the FiT scheme.
- Scheme combination 75/25, where 75% of the PV generated energy is fed into the grid and remunerated by means of the FiT scheme, while 25% is self-consumed by the customer.
- Scheme combination 50/50, half of the generated energy is fed into the network while the another half is self-consumed.
- Scheme combination 25/75. Only 25% of the generated energy is fed into the grid while 75% is self-consumed by the customer
- Scheme combination 0/100. All of the generated energy is self-consumed.

In addition, five types of PV systems have been studied, as follows:

- 5 kW PV power plant installed through a fixed array system.
- 100 kW PV power plant with a fixed array system.
- 100 kW PV power plant equipped with a dual-axis tracking system.
- 1 MW PV power plant with fixed array system.
- 1 MW PV power plant equipped with a dual-axis tracking system.

Given the possible combinations of the support schemes with the PV systems and the seven countries, a total of one hundred and seventy five scenarios have been studied in the work. Due to the huge volume of results, only the outcomes of four representative PV systems are provided in the paper:

- 5 kW PV power plant installed through a fixed array system, with a support scheme of 50/50. Therefore, model parameters $P_{1,t}$ and $P_{2,t}$ in the equation 2 are both equal to 0.5.

- 100 kW PV power plant with a fixed array system, with a support scheme of 75/25. Therefore, model parameters $P_{1,t} = 0.75$ and $P_{2,t} = 0.25$.
- 100 kW PV power plant equipped with a dual-axis tracking system, under a 100/0 support scheme. In this case, $P_{1,t} = 1$ and $P_{2,t} = 0$.
- 1 MW PV fixed array system, under a support scheme of 100/0.

In this sense, a residential PV power plant, a commercial and two utility owned power plants may be deduced. In addition, due to the widespread use of solar tracking systems in large PV power plants, a dual-axis tracking system scenario is taken into account for the two large PV power plants considered in this work (100 kW and 1 MW tracking systems). Several examples of large PV power plants equipped with dual-axis tracking systems is included in Moreton et al. (2015). Based on the analysis conducted in the work, the location of the country is another input of the model not only to take into account the different values of solar irradiation but also the costs associated with both the investment and the operation and maintenance of the PV power plant. Furthermore, the different costs of the electricity price paid by customers in the countries examined is also taken into account. Therefore, the total number of PV power plant scenarios considered in the present work is five in each country and five types of scheme combination analysed. It should be noted that each scenario will analyse different cases depending on the power flow direction, i.e., relation between energy injected into the power system and self-consumed generated solar PV power.

4.3. PV model parameters

The solar PV model parameters associated with the power plants are one of the most relevant inputs needed for the economic model developed. In this line, the PV parameters are composed of the solar radiation, efficiency of the PV power plant and PV panel degradation. These parameters are represented as β_i, η_s and γ_m, in Eq. 2, respectively.

Firstly, solar irradiation data are widely used for estimating the performance of solar energy systems. Several radiation databases are available, including free and commercial products. The present work uses the public information given by the Photovoltaic Geographical Information System (PVGIS) (EU, 2016), which provides an open access database of solar energy resource from PV systems in Europe, Africa, and South-West Asia. Indeed, this web application is now widely used by the PV community in Europe (Huld et al., 2010, 2012; Tyagi et al., 2013). In this regard, the first two columns of table 2 collect the solar radiation data considered in the present work depending on the corresponding country, in kWh/m^2. The table shows there are notable differences between the solar radiation received by a fixed array system and a two-axis tracking system. However, there is almost no difference in the solar radiation received between a single-axis and a dual-axis tracking systems. For this reason, both alternatives, a fixed and a dual-axis, are considered in the present work. In addition, some technical losses have to be considered to translate the incoming solar radiation into the electric energy output of the PV panel, in kWh per installed kWp. The irradiance and ambient temperature are the two main factors that affect the performance of PV modules (Akinyele et al., 2015), which vary strongly with the geographical location of the PV power plant (Huld et al., 2010). Therefore, the main losses to be taken into account are due to temperature and irradiance and due to angular reflectance effects as well as other losses (cables, inverter, etc). The energy performance of a PV power plant under real-life environmental conditions depends on the combination of these losses. In this sense, in parallel with the PVGIS data, the economic model developed in this paper considers the experimental data of a real PV power plant located in Spain, which has an installed capacity equal to 11.9 kWp. The yearly power generation of this PV installation is presented in Fig. 3, where it is deduced that total PV system losses are around 26%, i.e. $\eta_s = 0.74$, for this specific installation. From the combination of the data provided by the PVGIS and the field experimental data, the energy performance of the solar PV power plants is shown in the last two columns of table 2. This data has also been validated in some other exper-

Table 2: Solar radiation and energy performance data of the PV power plants considered, in kWh/m^2 and kWh/kWp, respectively.

Country	kWh/m^2 **Tracking system**		kWh/kWp **Tracking system**	
	Fixed	**Dual-axis**	**Fixed**	**Dual-axis**
Germany	1230	1560	940	1192
Italy	1680	2040	1273	1546
UK	1190	1490	912	1141
France	1440	1850	1092	1402
Spain	2040	2810	1510	2079
Belgium	1240	1570	944	1195
Greece	1890	2510	1399	1857

imental works carried out in Spain by other authors (de Cardona and López, 1998; Moreton et al., 2015).

Furthermore, PV modules are subject to different forms of degradation (Akinyele et al., 2015). The yearly reduction rate of the maximum power expected from a PV cell, module, array or system in the field is commonly referred to by the term degradation rate, γ_m in Eq. (2). Currently, most investors finance a solar system based on an assumed panel degradation rate between 0.5% and 1.0% per year (Cambell, 2008), which is according with historical measured data given for crystalline silicon PV panels (Phinikarides et al., 2014; Skoczek et al., 2009). It should be noted that modules are usually guaranteed for 25 years at minimum 80% of their rated output and sometimes for 30 years at 70% (IEA, 2014), while some manufacturers give a double power warranty for their products, typically 90% of the initial maximum power after 10 years and 80% of the original maximum power after 25 years (Devabhaktuni et al., 2013). Based on the previous findings, the present work assumes $\gamma_m = 0.8\%$.

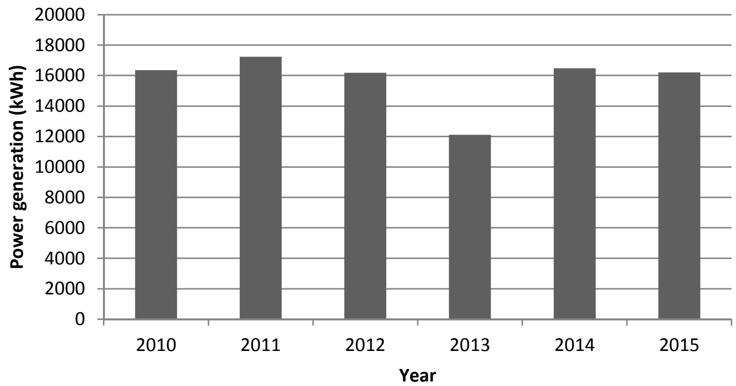

Figure 3: Yearly power generation of a Spanish PV power plant.

4.4. *Electricity market price parameters*

The price of energy depends on a wide range of parameters, including geopolitical situation, import diversification, electrical network costs, environmental protection costs and weather conditions. Commonly, the price paid by the end customer depends on the type of customer, i.e., residential customer, commercial customer or industrial customer. In this work, the electricity price, $e_{2,t}$ in Eq. (2), is based on the data published by *Eurostat* —the statistical office on the European Union—(Eurostat, 2016a), which publishes official, harmonized statistics of the European Union. The analysis of electricity prices for residential customers, associated with a 5 kW PV power plant in the present work, is based on prices for the medium standard household consumption band, which commonly presents an annual electricity consumption between 2500 and 5000 kWh. On the other hand, the analysis for industrial consumers, associated with either a 100 kW or 1000 kW PV power plant in this work, is based on prices for the medium standard industrial consumption band, which implies annual electricity consumption in the range between 500 and 2000 MWh. In this line, the electricity price considered for each country in the present work is shown in Table 3 (Eurostat, 2016a). It should be noted that electricity prices considered in this table include taxes, levies and VAT for household consumers; refundable

Table 3: Electricity market price depending on the type of customer, in €/kWh

Country	**Customer type**	
	Residential	**Industrial**
Germany	0.295	0.149
Italy	0.243	0.160
UK	0.218	0.152
France	0.168	0.095
Spain	0.237	0.113
Belgium	0.235	0.108
Greece	0.177	0.115

taxes and levies and VAT for industrial customers are excluded. As can be seen from Table 3, there is a considerable difference in the cost of the electricity paid by customers in different EU countries. German residential customers pay the highest price of electricity meanwhile Italy has the largest electricity price for the industrial use.

4.5. Upfront costs of the PV system

A detailed PV power plant cost analysis is conducted, based on a review of the scientific literature. The cost of different materials for solar cells are constantly decreasing through research and development efforts in the field of materials science. Nevertheless, cost reductions have not been steady. As previously mentioned in Section 2, the high demand for PV systems in different countries, in certain periods, created shortages in the supply of silicon for PV module production and put upward pressure on PV module prices. The PV power plants considered in this paper are assumed to be equipped with crystalline silicon (c-Si) modules as this is the most commonly used technology worldwide.

The cost analysis is divided into two different sources: upfront costs, which are addressed in the present subsection, and operation and maintenance (O&M)

costs, which will be discussed in the following subsection. Upfront costs are associated with the expenses charged at the onset of the PV power plant project. Renewable energy power plants can be described as having high upfront costs but low operation costs, which is in contrast to conventional fossil fuel power plants where investment costs are lower and variable operation costs are higher (Jäger-Waldau et al., 2011).

For most solar PV installations, the cost of PV panels and inverters can account for over half the costs (IRENA, 2012; Ossenbrink et al., 2013; Ventre et al., 2001; Wirth, 2016; Wiser et al., 2009). In 1996, the average price for c-Si modules was around 3.50 $€/W_p$ (Mah, 1998). Currently, c-Si panels in Europe have an average cost of around 0.62 $€/W_p$ (IEA, 2015b; UNEF, 2015). The other investment costs are basically the installation labour costs, other materials costs (components required for mounting and racking the PV system, electrical components...), overhead costs and regulatory compliance costs. Due to economies of scale, the size of the PV power plant has a notable effect on the cost of the installation. Smaller systems —several kW— exhibit higher installation costs per kW than larger systems —MW-range—, accounting for a 25% reduction in some cases (Tyagi et al., 2013; Wiser et al., 2009).

Upfront costs are also highly dependent on the country (Huijben et al., 2016; IEA, 2015c; Neubourg, 2014; Novák et al., 2011; Papadelis et al., 2016; Tselepis, 2015). According to the study conducted by Wiser et al. (2009), the installation cost for small PV systems in 2007 was larger in the U.S. than in Germany, which may be partly motivated by the greater cumulative grid-connected PV capacity in Germany compared to the U.S. This is in line with the information from the report of IRENA (2012), which shows that from 2009 PV panels are around 15% more expensive in EU than in the U.S.

Under this framework, it is clearly deduced that a different upfront cost must be considered for each country and PV plant size. For this purpose, Table 4 presents the installation costs associated with each PV power plant, in $€/W_p$. These have been considered as input for the calculation of the NPV in Eq. 4. These costs are related to the fixed array solar PV power plants considered in

Table 4: Upfront costs of the PV power plants considered, in €/W_p

Country	PV plant size (kW)		
	5	**100**	**1000**
Germany	1.75	1.35	1.03
Italy	1.70	1.20	1.14
UK	2.35	1.77	1.20
France	3.00	2.20	1.30
Spain	2.20	1.50	1.20
Belgium	1.80	1.40	1.10
Greece	1.50	1.20	1.00

this work —5 kW, 100 kW and 1000 kW—, while an increase in the installation costs of up to 26% is assumed for the dual-axis tracking system installations —100 kW and 1000 kW—. Furthermore, it should be noted that these upfront costs have also been validated through consultation with private companies with extensive experience in the solar PV sector.

4.6. PV power plant cost analysis: O&M costs

With regard to the operation and maintenance costs, a wide range of items need to be considered, such as general site management costs (road/building management, water/waste management...), electrical inspection costs (visual scanning, infrared thermography scanning, current-voltage curve analysis...), panel washing and vegetation control costs, inverter maintenance costs and insurance costs. According to data from U.S. utilities (Enbar and Key, 2010; Enbar and Weng, 2015), O&M costs typically account for between 1% and 5% of an MW-class plant's total upfront costs, which is in line with other contributions (Campoccia et al., 2014; Dusonchet and Telaretti, 2015; Moore and Post, 2008). In other words, O&M cost associated with a large PV power plants may vary between 8.85 €/kW_p and 53.13 €/kW_p per year, the latter value being related to power plants equipped with dual-axis solar tracking. On the other

Table 5: O&M costs of the PV power plants considered, in % of total investment cost

Tracking system	PV plant size (kW)		
	5	100	1000
Fixed	6.0	4.6	3.5
Dual-axis	—	4.9	3.7

hand, smaller PV systems are often between two and four times more expensive to maintain than large sites (Keating et al., 2015). Meanwhile, in Europe, where a more advanced PV economy is found, O&M costs tend to be 50-100% higher than in the United States (Enbar and Key, 2010).

Based on the previous data, Table 5 presents the O&M costs associated with each PV power plant analysed in the present work, as a percentage of initial investment. These have been considered as input for the calculation of the yearly expenses in Eq. (3).

4.7. Additional calculation assumptions

The following further assumptions have also been applied in the present work:

(i) FiT and NM are the only support schemes considered in the model calculations (no capital subsidies, tax reductions, loans or R&D incentives).

(ii) A period of 25 years is assumed as the life of the installation. Additionally, the amortization time has been considered with a residual value equal to zero at the end of its life cycle.

(iii) The inflation rate per country is taken from the Harmonised Indices of Consumer Prices (HICP) from Eurostat (2016b). These data are given in Table 6.

(iv) The VAT rates (see Table 6) are those in force in the seven countries as of 1 January 2016 (EC, 2016) .

(v) The WACC has been selected by country and as a function of the PV plant size (Cleantechnica, 2016). The values are detailed in Table 6.

Table 6: Economic and financial data in the selected EU countries

Country	HICP (%)	VAT (%)	WACC (%)		
			5 kW	100 kW	1 MW
Germany	0.1	19.0	3.0	4.5	4.5
Italy	0.1	10.0	6.0	9.0	9.0
UK	0.0	5.0	5.0	6.5	6.5
France	0.1	5.5	4.0	5.7	5.7
Spain	-0.6	21.0	7.0	10.0	10.0
Belgium	0.6	21.0	5.0	6.0	6.0
Greece	-1.1	13.0	8.0	12.0	12.0

(vi) The yearly insurance cost of the PV system is taken to be 1% of the yearly installation value after depreciation and amortizations.

5. Results and discussion

Having defined the theoretical model and having explained the variables used in the economic analysis, this section now provides the most relevant results related to the financial assessments of the PV systems with the selected scheme combination and the comparative analysis in the different countries. In addition, the model provides the minimum FiT price that makes the installation profitable. Note that all calculations have been computed with a FiT rate between 0.100 €/kWh and 0.300 €/kWh in order to make clear the presentation of the results. These FiT values have been selected as a consistent range due to the current FiT level in operation in the seven countries studied.

5.1. 5 kW PV systems results

With regards to the small PV systems, Fig. 4 shows the NPV for the 5 kW PV plant with the 50/50 scheme combination, by country. Five values for the FiT incentive have been considered, from 0.100 €/kWh to 0.300 €/kWh, in 0.050 €/kWh steps, and also the electricity price in each country —as collected in table 3— to evaluate the savings by means of the net-metering scheme. In addition, Fig. 5 shows the minimum value of the FiT price from which the project begins to generate a positive NPV. Fig. 6a) shows the evolution of the IRR along the evaluated FiT range and Fig. 7 shows the evolution of the payback. From the analysis of these figures, the financial and economic results for these small PV systems reveal the following:

- In general, considered small 5 kW PV power plants with a scheme combination of 50/50 are not suitable in three of the seven countries due to the low level of NPV obtained by the projects. Specifically, negative NPV have been obtained in France, UK and Belgium according to the FiT value, $e_{1,t}$ in Eq. (2): from -14.79 k€ to -6.79 k€ in France, -11.52 k€ to -5.53 k€ in UK and -6.85 k€ to -0.29 k€ in Belgium. Italy and Germany presents the best results for this PV system, with positive cash flows from a FiT of 0.150 €/kWh and Spain and Greece from a FiT value of 0.200 €/kWh.

- In Fig. 5 the values of the FiT minimum are represented according to the FiT/NM combination —$P_{1,t}$ and $P_{2,t}$ in Eq. (2)—. This figure shows the model results for all PV simulated systems, the seven countries and various types of scheme combination: 100/0, 75/25, 50/50 and 25/75. For the small PV 5kW fixed system, some findings can be obtained from Fig. 5. First, not all the countries have the same behaviour when the FiT/NM combination increases in favour of the NM scheme. Germany and Italy present the same pattern, showing the minimum FiT value decreases as long as the FiT/NM combination moves in favour of the NM scheme. By contrast, the other five countries present the opposite pattern, and with very high values for the FiT minimum in UK, France and Belgium where these type of PV systems seem to be completely unprofitable.

- Regarding the IRR results, Fig. 6a) represents the evolution of the IRR for a 5 kW fixed 50/50 PV system and the seven countries. Italy and Greece show the best profitability results, followed by Spain, Germany and Belgium. In view of the results for Italy and Greece, it can be observed that the IRR evolution is better for Italy until a FiT value of 0.200 €/kWh changing at this level in favour of Greece. Obviously, France and UK are not represented in the figure as the IRR results are negative for the FiT range considered.

- The PBP evolution of the 5 kW PV systems is represented in Fig. 7. Note that this figure represents the PBP evolution for the 5 kW PV fixed system and the five FiT/NM scheme combinations. Italy and Germany presents the most favorable PBP results for the 0/100 scheme combination (total NM scheme) with values of 13.90 years and 14.85 years respectively. The other five countries are not able to return the investment during the project life for this 0/100 scheme combination. With regard to the 50/50 scheme combination, Italy and Germany also presents the best results followed by Greece and Spain. For the 100/0 scheme combination, the best PBP results are obtained for Greece, followed by Italy, Spain, Germany and Belgium. UK and France present PBP values above 25 years. Similar results are obtained for the 75/25 scheme combination with the best results and very close values for Italy and Greece, followed by Germany, Spain and Belgium. Concerning the 25/75 scheme combination, the most favourable PBP results are obtained for Italy, followed by Germany, Greece and Spain.

Under this framework, the results show these small PV systems are most unprofitable in France and UK, where upfront costs are extremely high and the electricity market price is not high enough to balance the upfront costs in a compensation scheme like the proposed 50/50. In contrast, Italy, Germany and Greece are the most profitable countries for two main reasons: the solar irradiation levels in Italy and Greece are the highest of the seven countries (see Table 2) and WACC ratio in the case of Germany is more than favourable (Table 6). These results are in line with previous works by Dusonchet and Telaretti (2015) and Campoccia et al. (2014), where the results for the 3 kW BIPV plant show that the lowest profitability is obtained in France (IRR 2.26%

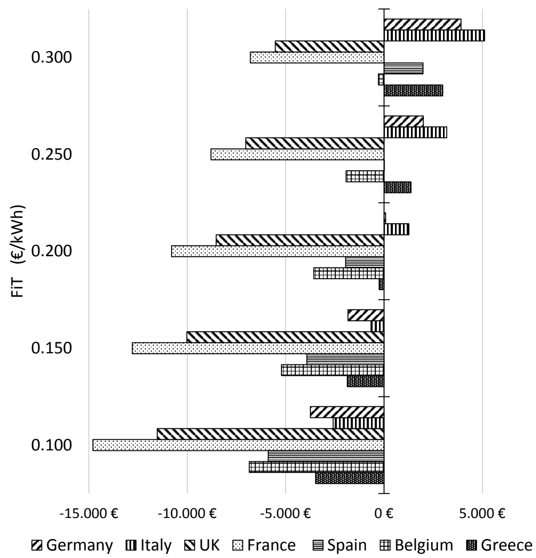

Figure 4: NPV for the 5 kW fixed PV system and 50/50 as scheme combination (per country).

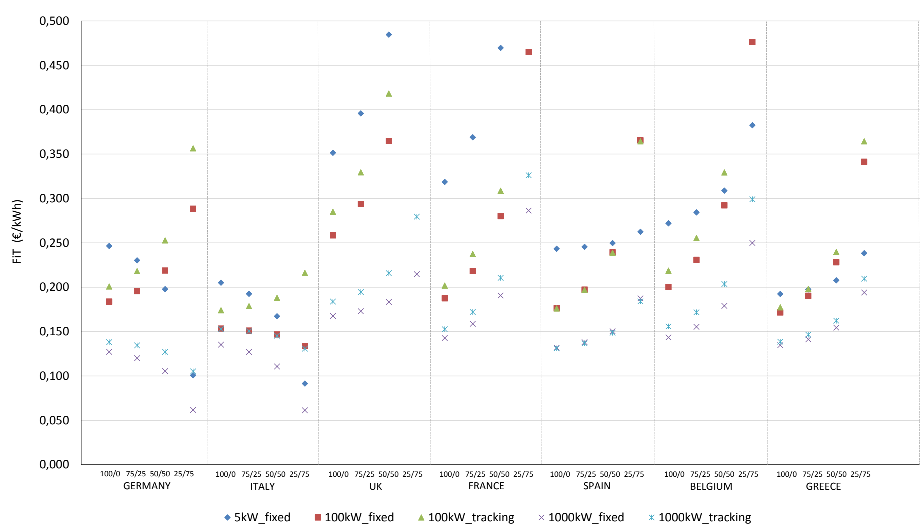

Figure 5: FiT minimum as function of the FiT/NM scheme combination, per country.

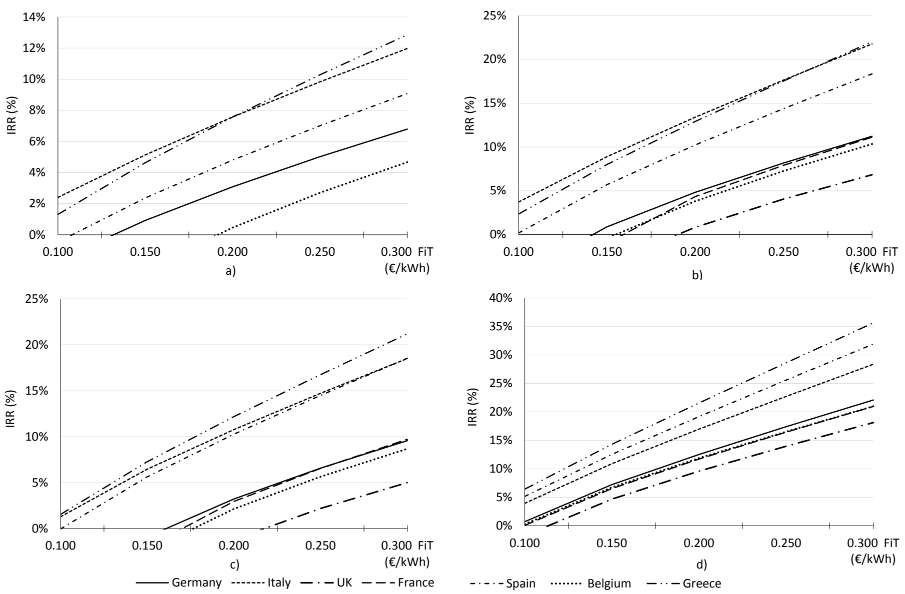

Figure 6: IRR for selected cases: a) 5 kW fixed 50/50, b) 100 kW fixed 75/25, c) 100 kW tracking 100/0, d) 1 MW fixed 100/0 (per country)

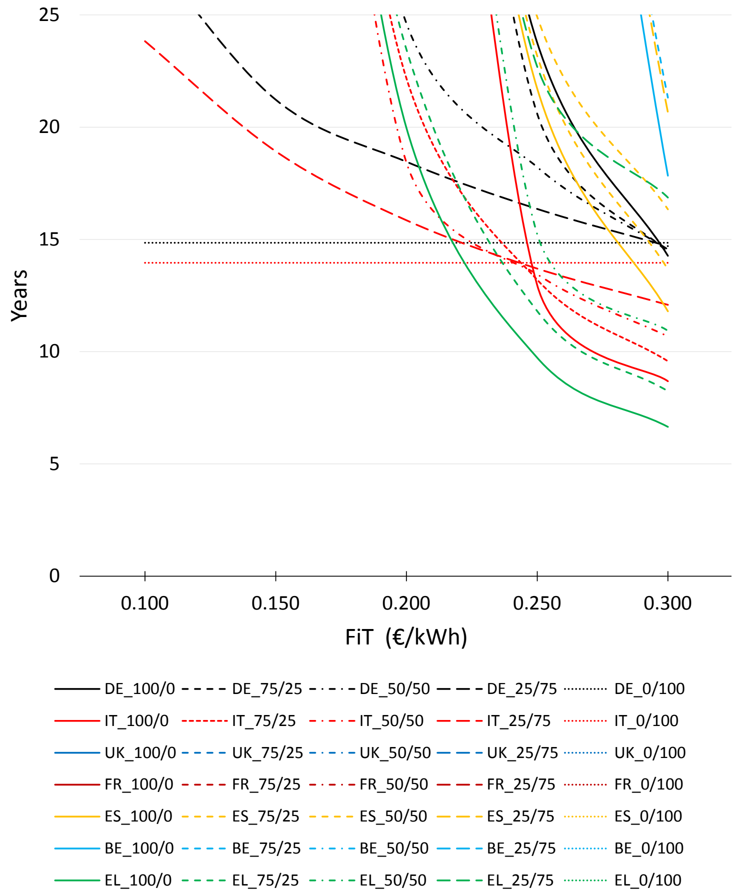

Figure 7: PBP for the 5 kW fixed PV system and FiT/NM scheme combination (per country)

and NPV -0.77 k€), while the highest profitability is found in Italy (IRR 9.1% with a NPV of 7.05 k€); Germany and Greece also show positive profitability. Note that the mentioned previous works consider the same WACC ratio for the seven countries (3%) in contrast to the present work where each country has its own WACC value as shown in Table 6. In addition, some differences could be due to the year used for the estimation of the data required by the model.

5.2. 100 kW PV systems results

Regarding the PV 100 kW power plants, two systems have been analysed in the present work: a 100 kW fixed PV plant with a scheme combination of 75/25 (it is a typical PV system in the roof of an industrial facility that consumes 25% of the total energy produced) and a 100 kW dual-axis tracking PV plant with a scheme mix of 100/0 (a small-medium ground-mounted solar power plant).

Figures 8 and 9 show the NPV results for these two types of 100 kW PV power plants in the seven countries. Fig. 5 shows the minimum FiT value for a profitable project. Fig. 6b and Fig. 6c include the IRR evolution for both systems. Fig. 10 shows the PBP evolution for the 100 kW PV fixed system in the seven countries. The following findings are deduced for these 100 kW solar systems:

- In relation to the NPV, Fig. 8 and 9 show the results for both 100 kW PV systems, for the seven countries and with a FiT range between 0.100 €/kWh to 0.300 €/kWh. For these PV systems, the UK presents the worst results for both installation types (-151.65 k€ to 4.79 k€ for the 75/25 fixed system and from -241.74 k€ to 19.44 k€ for the 100/0 dual-axis tracking system). Italy has the best NPV results for the 75/25 fixed systems and Spain for the 100/0 tracking system.

- Regarding the minimum FiT values for which the NPV is equal to zero, Fig. 5 shows the results for all the 100 kW PV fixed and tracking systems considered. Some patterns can be deduced from this figure:

  - All countries except Italy present a similar pattern for the 100 kW fixed systems, where the minimum FiT increases in parallel to the scheme combination once the NM ratio increases. In the case of Italy, the pattern is different since the FiT minimum decreases when the scheme combination is more favourable for the NM scheme. For the 100 kW tracking system all countries present the same pattern, increasing the FiT minimum in line with the combination scheme.
  - For all countries except Spain and Greece, the required FiT minimum for the 100 kW tracking systems is higher than the FiT minimum for the 100 kW fixed systems. Spain and Greece present very similar results for both fixed and tracking PV systems.

- Figures 6b and 6c show the evolution of the IRR results for both types of 100 kW PV systems: 75/25 fixed and 100/0 tracking. The first finding is that all countries improve their profitability results in relation to the 5kW PV systems. Additionally, the figures present similar results for both fixed and tracking systems. Italy, Greece and Spain present the best profitability results with some small obvious differences. On a second level, Germany, France and Belgium present very close IRR results, while the UK shows the lowest values but with positive profitability from a FiT of 0.190 €/kWh for the 100 kW fixed system and 0.220 €/kWh for the 100 kW tracking system.

- Fig. 10 shows the PBP evolution for the 100 kW PV fixed system with the five scheme combinations. It can be observed that the investment cost could be returned before 25 years in every considered country depending on the FiT/NM combination. Italy is the only one that obtains a PBP value lower than 25 years for all scheme combinations. The other countries have suitable PBP values for all scheme combinations with the exception of Germany for the 0/100 scheme combination, UK for the 50/50, 25/75 and 0/100 scheme combinations and France, Spain, Belgium and Greece for the 25/75 and 0/100 scheme combinations. The PBP results for the 100 kW

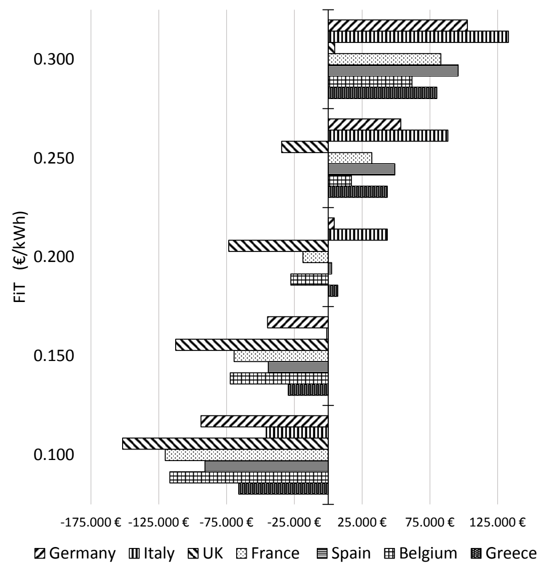

Figure 8: NPV for the 100 kW fixed PV system and 75/25 as scheme combination (per country).

tracking PV system are similar to the fixed PV system and consequently, this figure has not been included in the paper.

5.3. 1 MW PV systems results

The work considers one type of 1 MW PV system, the fixed type, as it is the typical medium-high solar farm in the EU market. The analyses for the NPV and IRR consider the 100/0 scheme, which is a common scheme for this type of solar power plant. PBP analysis and FiT minimum have been analysed for various scheme combinations.

The results for this PV system are presented in Fig. 11 for the NPV, Fig. 5 for the minimum value, Fig. 6d for the IRR evolution, and Fig. 12 showing the PBP evolution for all the 1 MW PV scheme combinations. Once again, the results are presented for all seven countries. The analysis of these figures provides the following results:

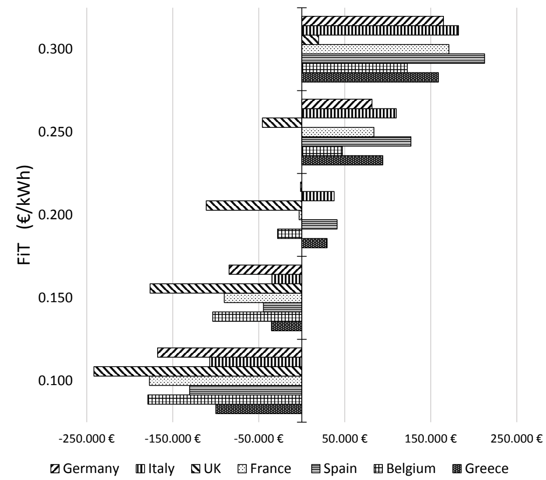

Figure 9: NPV for the 100 kW tracking PV power plant and 100/0 as scheme combination (per country).

- Concerning the NPV results, Fig. 11 shows that every country, except the UK, present positive results from a FiT value equal to 0.150 €/kWh and every country, including the UK, from a FiT value of 0.200 €/kWh FiT. It can be seen that Germany, Spain, France and Italy present the highest NPV results, followed by Belgium, Greece and finally UK. Initially, the results show that large PV systems are more attractive for investment investment than small and medium systems. This finding is in contrast to previous works by Dusonchet and Telaretti (2015) and Campoccia et al. (2014), whose results show that ground-mounted PV systems are less profitable than rooftop PV systems. Nevertheless, it is worth noting that the costs associated with PV power plants (both upfront and O&M costs) are in continuous evolution and authors in the present work have conducted a detailed review of the current PV costs. In addition, the WACC has a higher impact on the profitability results in large facilities than in small and medium plants.

- Regarding the minimum FiT values, Fig. 5 shows the model results for

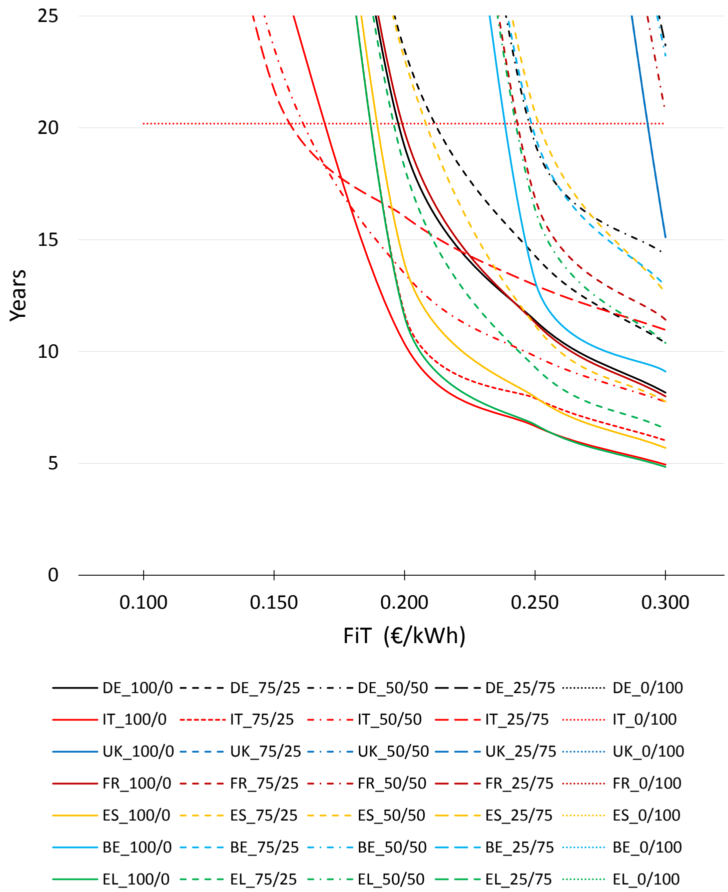

Figure 10: PBP for the 100 kW fixed PV system and FiT/NM scheme combination (per country)

all 1 MW PV fixed and tracking systems. As in the previous PV systems considered, some patterns can be deduced from this figure:

  - For all countries, these 1MW PV systems require a lower level of FiT than the other PV considered systems.
  - Germany and Italy present a similar pattern to that for the 5kW fixed PV system: the FiT minimum decreases once the FiT/NM combination is more favourable for the NM scheme. The other five countries present the opposite pattern.
  - For most of the countries, the required FiT minimum is higher for the tracking PV system than for the fixed type, the values being very similar for both Spain and Greece.

- In relation to the profitability analysis, Fig. 6d shows the evolution of the IRR results for the 1 MW PV system fixed under the 100/0 scheme combination. The results present similar patterns for every EU country considered. This type of PV system may be profitable in the seven countries with IRR values higher than the required WACC in all countries. Greece is the best country to invest in, followed by Spain, Italy, Germany, Belgium, France and UK.

- Finally, the PBP evolution for all the 1 MW PV systems have been evaluated and represented in Fig. 12. The PBP is less than 25 years for every EU country considered under each scheme mix. Moreover, all the countries have good PBP results from a reasonable FiT of 0.15 €/kWh.

Comparing the results obtained in the present work with the findings of Dusonchet and Telaretti (2015) and Campoccia et al. (2014) it can be observed that the results are very similar for the case of France. Comparative results for the 1 MW ground-mounted plant with 100/0 as support scheme (0.075 €/kWh as FiT) are -925.23 k€ for the NPV and -3.22% for the IRR, versus -918.22 k€ and -4.76% as the results of the present work. However, the case of Greece is

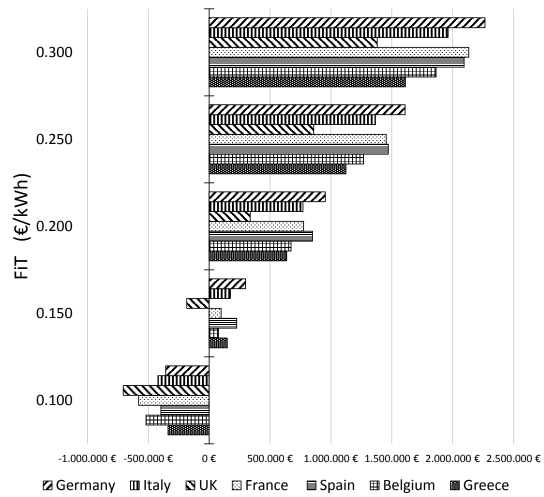

Figure 11: NPV for the 1 MW fixed PV power plant and 100/0 as support scheme mix (per country).

quite different mainly due to the WACC considered. For a FiT of 0.09 €/kWh and 100/0 as support scheme, the results in the above mentioned works are 209.54 k€ and 4.4% as opposed to those obtained in the present work for the same FiT (-581.6 k€ and -1.72%). The comparative results for the other countries have similar differences in some cases. Again, these differences are based on the different years considered for the calculation and the differences in the WACC values.

6. Conclusions and policy implications

This paper has presented a model for comparative cost-effectiveness assessment of PV systems with different combinations of feed-in tariff (FiT) and net-metering (NM) schemes. The model takes into consideration all the factors that could affect the profitability of a PV power plant, such as legal, financial, economical, technological and geographical factors. Feed-in tariff and net-metering schemes are mixed to different degrees in order to evaluate the best combination of these mechanisms to produce a profitable plant. The model has been used to

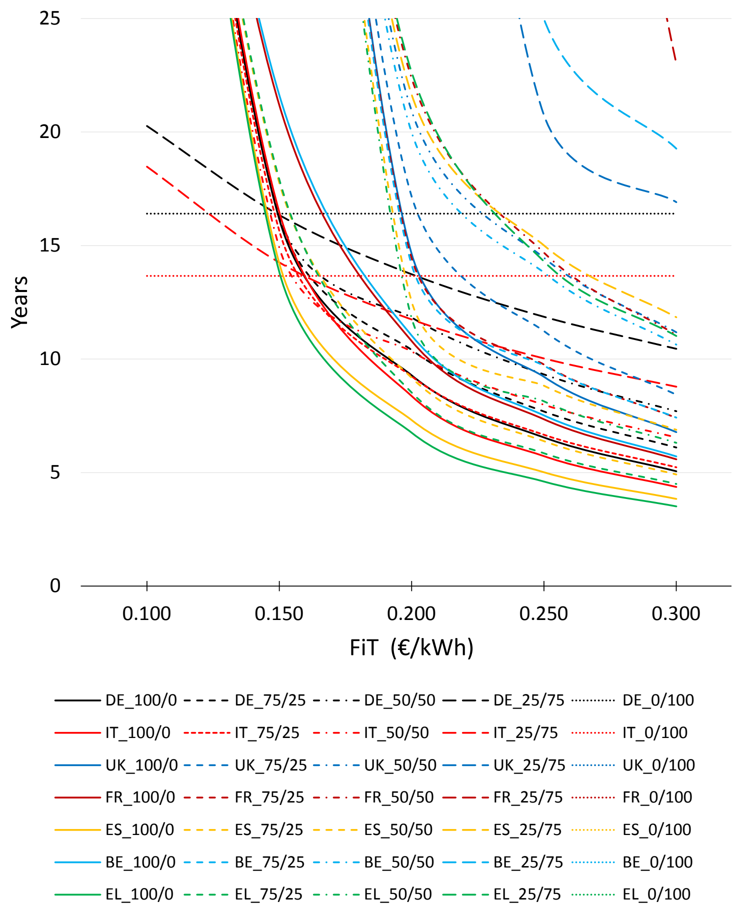

Figure 12: PBP for the 1 MW fixed case and FiT/NM scheme combination (per country).

perform a comparative analysis of the profitability in the seven countries with the largest PV installed capacity in Europe. Over the last fifteen years, these countries have produced 85.7% of the total PV installed capacity share. The main conclusions and policy implications from the present work are summarised below.

First, a combination of feed-in tariffs with net-metering schemes is a viable option for PV development in most of the countries considered using the PV systems studied and adopting suitable levels of tariff prices. The work offers a complete analysis of the alternatives that could be economically profitable in each country and within a feasible level of FiT prices.

Second, the results show that this renewable energy generation system is not profitable in most cases without the support of an electricity compensation scheme. The results are favourable only once the FiT price rate achieves a greater level than the electricity costs. It is for this reason that a full net-metering or self-consumption scheme will be feasible only once upfront costs are low enough to make PV energy economically profitable or when electricity prices are high enough to balance these costs.

Third, plant size seems to be a key factor with a significant impact on profitability owing to the considerable decrease in upfront costs with plant dimensions. The results provide evidence supporting the fact that larger solar plants are more profitable than medium and small systems.

Fourth, Germany, Italy, Spain and Greece seem to be the most attractive countries to invest in PV projects mainly due to favourable financial conditions in Germany and the excellent solar irradiation levels in Italy, Spain and Greece. Moreover, high electricity prices, mainly in Spain and Italy, tend to favour this type of combined schemes. In these countries, the net-metering or self-consumption schemes should prove attractive to potential consumers. Spain may activate its self-consumption law for the benefit of "prosumers". In contrast, the UK and Belgium show the weakest economic profitability results. PV development in these countries seems to have been mainly promoted by the high level of compensation provided by the government. In the case of France, the results are more favourable for large plants than for medium and small units, which seem to be unprofitable.

Fifth, concerning the upfront costs of PV power plants, the results support the fact that the initial investment is still too high to allow PV energy to be economical without additional support. Actions should be implemented to reduce upfront costs by using new materials or new technologies.

The work presented in this paper may help the authorities in the countries analysed to make efficient decisions concerning where, how and under what conditions PV policies should be promoted. Furthermore, the sensitivity analysis of the main variables discussed in this paper could help to guide future decisions.

Further work could focus on a comparative analysis taking into consideration other technological parameters such as the PV module type. An assessment of other geographical areas and the extension of the model to enable the evaluation of other types of RES projects, such as wind energy, might also be conducted.

Abbreviation	**Definition**
BIPV	Building-integrated Photovoltaics
CF	Cash Flow
EC	European Commission
EU	European Union
FiT	Feed-in Tariff
FiP	Feed-in Premium
HICP	Harmonised Indices of Consumer Prices
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	The International Revewable Energy Agency
IRR	Internal Rate of Return
NM	Net-metering
NPV	Net Present Value
O&M	Operation and Maintenance
PBP	Payback Period
PV	Photovoltaic Energy
PVGIS	Photovoltaic Geographical Information System
RE	Renewable Energy
RES	Renewable Energy Sources
SC	Self-consumption
UN	United Nations
VAT	Valued Added Tax
WACC	Weighted Average Cost of Capital

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