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On the Cost of Photovoltaic Electricity for Small Residential Plants in the European Union

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Abstract- The substantial decrease in the cost of photovoltaic panels has made this renewable source of energy competitive with respect to conventional sources. As a result grid parity seems now within reach in many member states of the European Union. This paper tries to make an assessment of the actual cost of photovoltaic electricity in each country of the Union using the Levelized Cost of Energy (LCOE) as the benchmark to compare with the actual price of electric energy. It is found that nowadays grid parity is effectively an issue in several different countries of the Union and that suitable supporting measures, apart from the Feed-In Tariff (FIT), could be used to further support the diffusion of this type of energy.

Keywords Photovoltaic; LCOE; Grid Parity; Feed-In Tariff, Renewable Energy, Energy Policy.

1. Introduction

At present, in the European Union (EU), photovoltaic (PV) energy accounts for almost 2.6 % of the whole 3100 TWh electric energy demand that the Union requires, yearly, for its life [1]. This figure has been continuously increasing during the last decade, mainly as a result of the combined effects of the adoption of national ad-hoc measures to support the diffusion of this specific renewable source of energy, such as the PV Feed-In Tariff and of the decrease in the cost of the photovoltaic solar panels, primarily the result of the China entry into this industrial sector [2].

The PV sector has now globally reached a good maturity characterized by a constant growth of about 30 GWp/yr for the last three years, a trend which seems confirmed also for the year being [3]. As a result, the actual effectiveness of supporting measures, such as the FIT, is more and more argued and, in the Union, a scientific, technical and political debate is now running aiming at finding suitable financial schemes, sustainable from the point of view of public spending, to support a sector that has become relevant for the Union industrial and environmental policies [4-6].

This work tries to assess the cost of the photovoltaic energy for small, roof-type, residential photovoltaic plants (3 kWp) and to compare it with the actual cost of electricity from conventional sources, in each member state of the Union. In EU small residential photovoltaic installations account for almost 21% of all the PV plants and play a key role in sustaining the diffusion of this form of energy since they are very capillary widespread (there is almost one small PV installation for each 50 European citizens) and the cost of residential electricity is generally high enough that grid parity, i.e. the moment when solar PV generation costs equal the price of electricity for final consumers, is more reasonable at a hand for this type of application [1]. It will be shown that for small residential PV applications, grid parity is already a de facto state in several member states of the Union and two supporting schemes, other than the FIT, which could be adopted with a possible positive effect on the development of this sector, will be discussed.

2. Methodology

In order to evaluate the cost of the PV energy in the member states of the Union, the photovoltaic Levelized Cost of Electricity will be considered as a benchmark. LCOE is simply defined as:

$$\mathrm{LCOE} = \frac{\text{Total life time PV plant cost}}{\text{Total life time PV plant energy production}} \quad (1)$$

According to Branker, Pathak and Pearce [7] a general, practical expression for LCOE is:

$$LCOE = \frac{\sum_{t=0}^{nt} (I_t + O_t + M_t + F_t)/(1+r)^t}{\sum_{t=0}^{T} E_t /(1+r)^t} \quad (2)$$

where I_t is the ratio between the total investment costs and n_t, the PV plant lifetime in years, O_t and M_t are respectively, the operation and maintenance costs in the year t, F_t are the costs to be paid for interests, E_t is the energy produced in the year t and r is the discount rate. In the following we will only discuss the r = 0 case. Also inflation will be neglected and loan term will be taken, to simplify, as equal to the plant operative lifetime. Finally, the whole energy produced by the PV installations here investigated is assumed to be either fed to the grid or self-consumed so that, in Eq. 2 the cost of energy storage by means of batteries can be neglected [8]. Under such assumptions LCOE can be rewritten as the ratio between the total investment cost, C_{tot} and the total energy produced in the n_t years of PV plant operation, E_{tot} as:

$$LCOE= C_{tot} / E_{tot} \quad (3)$$

and if τ is the interest rate then Eq. 3 can be simplified as:

$$LCOE = \frac{C_0 * (1+\tau)^{nt} + C_1}{(PVP_{np} * \eta_{SYS} * H * \sum_{1}^{nt} (1-d)^{j-1})} \quad (4)$$

Here C_0 are all the initial capital sensitive costs, C_1 are all the costs accrued along the PV plant lifetime, PVP_{np} is the nominal PV plant power expressed in kWp while η_{sys} is the system efficiency whose value can be assumed, nowadays, between 80% and 90%, H are the annual sun hours in the site where the PV plant is located and, finally, d is a degradation term, taking into account that during the 25 years of PV plant operating lifetime, panels conversion efficiency tends to diminish mainly as a result of the interaction with the environment [9]. Degradation can be considered linear with time at any practical purpose and, in general it can be assumed d=0.7%/yr for the solar technologies here considered.

As far as C_0 is concerned, all the initial capital sensitive costs can be expressed by: $C_0=C_{pan}+C_{BOSp}+C_{BOSa}+ C_{add}$.

C_{pan} is the panels cost. Here we'll mainly refer to crystalline Silicon and poly-Silicon based panels whose costs have rapidly decreased during the last 3 years so that it is now easy to find panels starting from 0.6 €/Wp up to 1.0 €/Wp, VAT excluded [10,11].

C_{BOSp} takes into account all the costs depending on the PV plant nominal power, that is wiring, switch gears, fuses, ground fault detectors, charge controllers, batteries, and inverters. Since we focus on grid-connected plants, battery costs will not be considered. Inverters cost plays, in this frame, the major role and is in the range from 100 €/kWp for large scale utilities up to 400 €/kWp for small residential applications [12-14].

C_{BOSa} are all the costs more directly depending on the PV plant surface such as the cost of the supporting structures or those related to the components transport up to the installation site. Here we discuss roof type PV plants which are supposed to be the most diffused type for a small residential installation. For roof-type PV plants the supporting structure cost can vary between 10 €/m^2 to 20 €/m^2, according to the different type of roof (flat or pitched). Installation costs of the plant are in the range of 100 €/m^2 while transport costs may range from 5 €/m^2 to 10 €/m^2 for any 100 km transportation [15]. The panel weight varies from 10 kg/m^2 up to 15 kg/m^2 comparable to what is available in the markets products.

C_{add} takes into account the costs of plant design, test and start-up as well as the installation profits. They can be expressed as a fraction, around 20%, of $C_{pan}+C_{BOSp}+C_{BOSa}$.

As stated, C_1 are all the costs accrued along the PV plant lifetime. They can be yearly costs, such as those related to land rental, costs encountered only after a number of years as it is the case for those related to inverters replacement or, finally, they can be costs occurring only at the end of the plant operating lifetime (that is even after 25 years) as it is for those related to plant dismantling and recycling. In general C_1 can be expressed as: $C_1= C_{RENT}+C_{O\&M}+C_{DISM}+C_{REC}$ and will be considered as fixed along the whole plant operating lifetime.

C_{RENT} are the overall costs related to land renting for the realization of ground mounted plants. For the cases under investigation (rooftop plants) they will be thus assumed as zero.

$C_{O\&M}$ are the yearly operation and maintenance costs. Values ranging between 0.4% up to 1% of the total PV plant cost have been reported with a minimum given by the cost for inverters replacement (at least once if n_t > 15 years), that is even 400 €/kWp for small residential applications while for larger applications, inverters cost may be much lower (up to 100 €/ kWp). It is worth to recall, in this respect, that inverter prices have halved during the last ten years [12, 13].

C_{DISM} are the dismantling costs and are computed assuming that the PV panel dismantling is similar to a glass window dismantling, evaluated at 6 €/m^2 for the glass and 1 €/m^2 for the supporting structure and that the transport from the PV plant site up to a 20 km far away collection point costs about 3 €/m^2. All the materials resulting from demolition works are intended to be brought to a generic waste landfills at a cost of 100 €/t - 200 €/t.

Finally, C_{REC} are the costs strictly related to recover and recycling of the PV plant materials and components in agreement with the Waste Electrical and Electronic Equipment Directive (WEEE) obligations [16], which fully equated photovoltaic panels to electronic consumer equipments. In particular C_{REC} refers to the costs related to the panels recycling since this part is normally, far more relevant than the others PV plant WEEE equipments (inverters, wiring, switch gear, fuses, ground fault detectors, charge controllers). A detailed analysis of C_{REC} shows that, for the case under investigation, a value of about 200 €/t can be taken for it [17].

Table 1. The various costs for a small residential PV plant (taxes excluded).

		C_0 (€)						C_1 (€)			
	Area (m^2)	C_{PAN}	C_{BOSp}	C_{BOSA}			C_{ADD}	C_{RENT}	$C_{O\&M}$	C_{DISM}	C_{REC}
				Supp. Structure	Transport	Instal					
3kWp roof type	20	1800	1200	300	200	2000	1100	0	2500	200	70

It is worth to note, however, that although the WEEE costs can greatly vary due to a number of different situations and variations even larger than 100% have been actually observed in several cases for the case under investigation C_{REC} and C_{DISM} play a minor role in the determination of the final PV plant cost [17].

3. Results and Discussion

3.1 Effect of Interest Rate, Degradation and PV Plant Lifetime on LCOE

In Table 1, the different costs defined above have been reported for the case of a residential 3 kWp roof type PV plant. All the costs are in €, excluding taxes. The PV plant lifetime considered is 25 years and the PV panel cost assumed is 0.6 €/Wp which is the cost for a PV panel (Chinese manufacture, May 2014, small installations) [10]. It is worth to note that this cost is however higher than the cost the EU Commission has recently agreed with Chinese producers after antidumping measures have been adopted by the Commission itself (0.53 €/Wp-0.56 €/Wp) and that therefore cheaper panels could be found on the market [18] .

As far as C_0 is concerned, all the data reported in Tab. 1 can be considered as identical in each member state of the Union except for the transport and installation costs that, being primarily labour cost sensitive, are expected to vary, considerably in the Union. Those reported in Table 1 refer to Italy [15] but, for all the following discussions, the hourly labour cost, in each member state of the Union, has been considered according to data reported in Table 2 [19]. Strictly speaking also C_{add} is partly dependent on the labour cost but for a simple, small residential PV application the labour dependant costs of plant design, test and start-up can be considered as negligible and included, at any practical purpose, into the installation profit above defined. C_1 is more complex to model since its final value depends on a number of different items, partly also related to the labour cost, whose trends in the 25 years of plant lifetime are very difficult to assess. For instance, following the cost trend observed in the last years, inverters price is expected to further decrease in this time range while, as a result of the European Union socio-economic policies, labour cost is supposed to increase tending to level off in any of the member states. Here we'll assume therefore for C_1 the highest value resulting from its definition. Again this assumption will therefore yield a superior extreme for the evaluated LCOE.

Let us now discuss some general features of Eq. 4 for the case under investigation, with respect to interest rate, solar panel degradation and PV plant operating lifetime dependences.

In order to study the effect of the interest rate, the Levelized Cost of Electricity from Eq. 4 has been normalized for the case when the interest rate is zero (τ=0):

$$LCOE_{\tau} \Big/ LCOE_{\tau=0} = \frac{(1+\tau)^{nt} + \frac{C_1}{C_0}}{(1+\frac{C_1}{C_0})} \quad (5)$$

Eq. 5 does not depend anymore on the energy produced by the PV plant and, since for the case under discussion the ratio C_1/C_0 can be assumed for any practical purpose equal to 0.4, (see Table 1), the effect of the interest rate can be more easily investigated.

In Fig. 1 the ratio $LCOE_{\tau} \Big/ LCOE_{\tau=0}$ has been then reported vs. the interest rate in the range 0%-10% assuming an operative PV plant lifetime of 25 years. As it can be observed, the interest rate plays a very critical role in the determination of LCOE and an almost eightfold increase is exhibited for an apparently modest 10% increase of the interest rate.

The effect results from the power law dependence the LCOE exhibits with respect to the interest rate but it is made so evident due to the long, 25 years, operating lifetime that characterizes the PV plant.

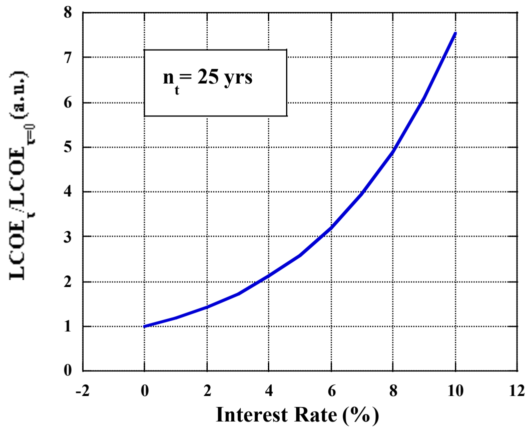

Figure 1. The ratio $LCOE_{\tau} \Big/ LCOE_{\tau=0}$ vs. the interest rate in the range 0%-10% for 25 yrs, PV plant operating lifetime

A similar approach has been used to investigate the effect of d, the panel degradation term. In Eq. 6 the Levelized Cost of Electricity from Eq. 4, has been normalized for its value at d=0:

$$LCOE_d / LCOE_{d=0} = \frac{n_t * d}{(1-(1-d)^{n_t})} \quad (6)$$

Again this expression does not depend anymore on any of the particular plant characteristics, but, as otherwise expected, only on the value of the degradation term and on the operating plant lifetime. In Fig. 2 this ratio has been reported vs the degradation term from 0.1%/yr up to 1%/yr.

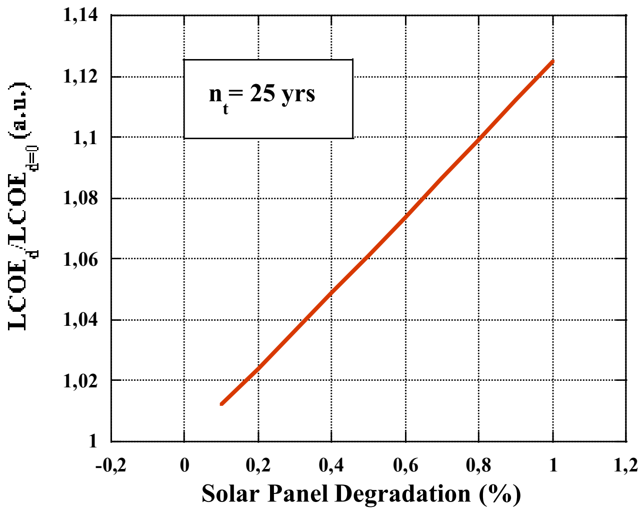

Figure 2. The ratio $LCOE_d / LCOE_{d=0}$ vs. the degradation in the range 0.1% - 1% for 25 yrs, PV plant operating lifetime

Data show that the effect of panel degradation is fairly much less relevant than the effect of the interest rate so that, even in the worst case, only a modest 10% increase in the LCOE value is observed.

The reason why panel degradation plays a minor role in LCOE determination obviously lies in its very low absolute value. A 1%/yr degradation means that the solar panel performances are only slightly affected, by less than 1%, after one-year of continuous operation, a result that only a very mature and reliable technology can offer.

Finally, in order to study the effect of the PV plant lifetime, Eq.4 has been evaluated using the data reported in Table 1 for the special case d=0. Under this hypothesis, that is expected to only negligibly affect the actual LCOE value, Eq.4 becomes:

$$LCOE = \frac{C_0 * (1+\tau)^{nt} + C_1}{(PVP_{np} * \eta_{SYS} * H * n_t)} \quad (7)$$

Eq. 7 shows that, as far as the PV plant operating lifetime is concerned, two opposite effects compete to control the LCOE value: a decrease due to the increasing energy production of the PV plant for increasing n_t and an increase of the cost, mainly related to the effect of the interest rate. In order to study the effect of the operating plant lifetime, LCOE in Eq.7 has been normalized for its value at n_t=1.

$$LCOE_{nt} / LCOE_{nt=1} = \frac{(1+\tau)^{nt} + \frac{C_1}{C_0}}{((1+\tau) + \frac{C_1}{C_0}) * n_t} \quad (8)$$

In Fig. 3 LCOE is reported vs the PV plant operating lifetime for different values of τ.

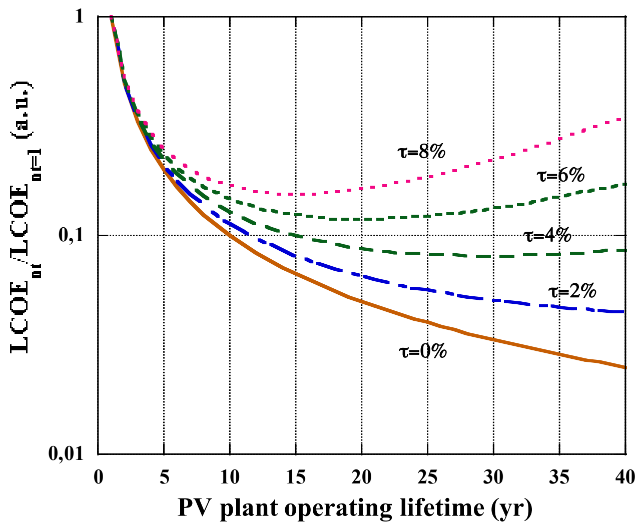

Figure 3. $LCOE_{nt} / LCOE_{nt=1}$ vs. PV plant operating lifetime in the range 0-40 years for increasing values of the interest rate from 0% up to 8%

For small values of the interest rate, the increase in energy production tends to dominate and a monotonic decrease of LCOE with n_t is observed. But, for increasing τ, the increase in energy production cannot anymore compensate the effect of the interest rate, the behaviour reverses and, eventually, a minimum could be even observed. The effect results from the power law dependence of the interest rate with respect to the plant lifetime compared to the corresponding linear increase of the PV plant energy production. Since the solar panel degradation mainly affects the energy productivity, it is reasonable to assume that, given an interest rate, for increasing d, the minimum will move towards correspondingly lower values of n_t.

3.2 The cost of PV electricity in the European Union member states

In Table 2 for each member state of the European Union, all the relevant data required to evaluate the LCOE according to Eq. 4 are reported. The actual electric energy price refers to household users whose annual consumption is less than 5000 kWh and includes all taxes, levies and Value-Added Tax (VAT) [20]. In EU an average constant increase of the order of 3 %/yr of the electricity prices has been observed in the last five years, an effect that, for the sake of simplicity, this study will neglect [21]. For the VAT, data have been taken from reference 22. For the hourly labour cost, we have taken the data referred to the Construction sector and,

Table 2. Data used in this analysis and the LCOE values evaluated under the investigated scenarios.

	Electric Energy Cost[20] (€/kWh)	Hourly labour cost[19] (€)	VAT[22] (%)	τ[23] (%)	Yearly Sunny Hours[24] (hrs/yr)	LCOE (€/kWh)	LCOE (VAT included) (€/kWh)	LCOE (ITC scheme, VAT included) (€/kWh)
Belgium	0,233	33,6	21	2,16	1080	0,236	0,285	0,243
Bulgaria	0,085	2,8	20	3,44	1500	0,140	0,168	0,151
Czech Republic	0,15	9,5	21	2	1150	0,156	0,189	0,162
Denmark	0,3	34,6	25	1,57	1100	0,208	0,260	0,217
Germany	0,26	24,6	19	1,46	1130	0,176	0,210	0,175
Estonia	0,11	9,9	20	NA	1130	NA	NA	NA
Ireland	0,215	25,5	23	2,9	1070	0,251	0,309	0,271
Greece	0,134	14	23	6,2	1650	0,274	0,338	0,317
Spain	0,182	20,3	21	3,11	1820	0,144	0,174	0,153
France	0,141	30,6	20	2,03	1450	0,165	0,198	0,169
Croatia	0,14	7,9	25	4,41	1490	0,188	0,235	0,215
Italy	0,219	26,5	22	3,23	1650	0,177	0,215	0,190
Cyprus	0,278	14,4	19	6	1950	0,224	0,267	0,250
Latvia	0,139	5,9	21	2,8	1150	0,171	0,207	0,183
Lithuania	0,126	5,8	21	3,26	1140	0,188	0,228	0,203
Luxembourg	0,17	23,6	15	1,71	1130	0,183	0,210	0,177
Hungary	0,158	6,2	27	5,56	1380	0,249	0,317	0,295
Malta	0,17	9,5	18	2,93	2000	0,107	0,126	0,112
Netherlands	0,186	32	21	1,85	1080	0,217	0,263	0,222
Austria	0,198	30	20	1,77	1350	0,167	0,201	0,169
Poland	0,142	6,4	23	4,1	1140	0,225	0,276	0,251
Portugal	0,199	10,3	23	3,82	1900	0,136	0,168	0,151
Romania	0,105	3,8	24	5,15	1520	0,198	0,246	0,228
Slovenia	0,154	11,4	22	3,52	1300	0,191	0,233	0,209
Slovakia	0,172	8,3	20	2,47	1250	0,154	0,185	0,161
Finland	0,155	33,2	24	1,84	1050	0,226	0,281	0,237
Sweden	0,203	38,5	25	2,06	1060	0,248	0,311	0,264
United Kingdom	0,168	23,1	20	2,3	1070	0,216	0,259	0,223

whenever they were not available (as it was for Greece and The Netherlands) the average hourly labour cost for the whole economy of the country, was assumed [19]. The interest rates used, are European Central Bank data updated to April 2014 [23]. Finally the sunny hours for each state member have been obtained by the yearly global irradiation data assuming standard AM1.5 conditions [24].

Using the data reported in Table 1 and in Table 2, LCOE values for each member state have been computed using Eq. 4, for a 25 years plant operating lifetime. The values, VAT excluded and included, are reported in Table 2. In Fig. 4 the computed LCOE values, VAT included, have been compared with the actual prices of electricity reported in the same Table, colouring each state of the Union according to the result of the comparison: whenever the LCOE value is lower than the electricity cost, green has been used while red marks the completely reverse situation. Yellow and orange mark intermediate situations (see Fig. 4 caption).

Figure 4. Comparing LCOE (VAT included) with the actual electricity price in the various member state of the Union. In green the countries where grid parity for small PV residential plants has been already reached, red marks the opposite situation while yellow and orange represent situation where differences within 10% and 20% respectively, can be found

Data in Table 2 show that both interest rate and yearly sun hours primarily determine the value of the photovoltaic electricity cost in a given country. The comparison map in Fig. 4 shows that in seven countries: Denmark, Germany, Spain, Italy, Cyprus, Malta and Portugal the grid parity is already a de facto state, even if no subsidizing FIT scheme were adopted. Noticeably three of them, Spain, Italy and Germany, are also those where the PV energy is the most diffused in terms of installed capacity. Moreover in two more countries, Austria and Slovakia, the difference between the actual electric energy price and the corresponding LCOE value is less than 10% (in yellow) and for other six countries, Belgium, Czech Republic, Ireland, Luxemburg, France and The Netherland, the relative difference is less than 20% (orange). This means that relatively light supporting FIT schemes should be probably sufficient, in most of the cases, to match the grid parity in half the countries of the Union, at least as far as small residential PV plants are considered. Actually, however, the situation should be even more positive than the one here above depicted since, to take into account and minimize the effect of the several uncertainties affecting the LCOE determination above discussed, the methodology used has effectively returned a superior extreme for LCOE. It is furthermore interesting to observe that the photovoltaic electricity costs obtained in this study well agree with the findings of A. Zhang and co-workers that similarly conclude their analysis observing that FIT schemes in EU could be considerably reduced or even eliminated in the near future [25].

As above recalled, the sustainability of any FIT scheme is now widely under discussion and an intense debate is running on the availability of alternative financial measures, more sustainable for public spending. In this respect the possibility for household owners, where a small PV plant is installed, to buy and sell the produced photovoltaic energy in a VAT exemption scheme, could actually be an interesting option. In Fig. 5 the comparison map has been re-evaluated for this special case where it is assumed that the LCOE values are VAT exempt. It is worth to note that, for any practical purpose, four more countries can be considered to enter, under this condition, the (green) grid parity state: Belgium, Czech Republic, Slovakia and Austria. Ireland, France, Luxemburg and The Netherland would show now differences within 10% while Slovenia, Sweden, Croatia, Latvia and United Kingdom were within the 20% limit.

Figure 5. Comparing LCOE (VAT excluded) with the actual electricity price in the various state members of the Union. Colours legend as in Fig.4

Data in Table 2 show moreover that this supporting scheme is very similar, in terms of its effect on LCOE, to the US Solar Investment Tax Credit (ITC), a mechanism, that allows individuals or businesses that purchase solar energy technologies to get a 30% reduction of the tax liability and whose application in EU would result in the LCOE values reported the last column [26]. VAT exempt and ITC have, however, quite different meanings. Reducing VAT on the PV electricity produced could in fact both open the way to a real energy trading for the simple household owners and result in a sort of social benefit since the whole community could advantage from the cost reduction. Both the effects could therefore cooperate to promote, in turn, the diffusion of this renewable form of energy. The ITC scheme, vice versa, does not basically change the approach to the support of the photovoltaic sector and, consequently, would not basically change the terms of the current debate on the effect that FIT measures, adopted in EU, have on the member states public spending.

4. Conclusions

In conclusions it has been demonstrated in this paper, that the interest rate plays a key role on LCOE determination and that, as a consequence, the most efficient and sustainable support to the PV sector in EU comes from the economic (and, in turn, political) stability of the Union itself. Eq. 4 clearly shows in fact that, for $\tau=0$, the grid parity would be actually reached in the greater part of the member states of the Union.

Moreover it has been found that even without the adoption of FIT supporting schemes, as far as small residential PV plants are concerned, grid parity has been already reached in several states member of the European Union and that for many others the difference between PV LCOE and the electric energy price is, at most, less than 20%. VAT exemption schemes, as an alternative to the actual FIT supporting policy, has been proposed and, finally, its effect on the grid parity issues has been discussed.

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