QUANTITATIVE ANALYSIS OF THE MERIT ORDER EFFECT FROM PHOTOVOLTAIC PRODUCTION IN ITALY

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ABSTRACT: This study proposes a method to quantify the savings incurred by the end consumers in Italy over the past 7 years as a result of the decrease in electricity spot market prices observed when PV plants feed electricity into the grid. The study showed that the total electricity demand retreated by PV production is well correlated to market prices, following a stable exponential curve. Estimating such curve enables to calculate what the additional energy payments would have been had there been no PV production. Such gain, called merit order effect, has varied over time. The authors have run Monte Carlo simulations on a large number of irradiation profiles and showed that the merit order effect does not depend much on the PV penetration rate but rather on the electricity demand profile, and therefore on how well it correlates with the PV production profile. The social gain expressed per MWh of PV electricity fed into the grid exceeds 100 €/MWh, and has exceeded € 2 Bn at the country scale in 2012. If that money could be captured by the government, it could be used to finance support schemes and grid infrastructure works for instance.

Keywords: economic analysis, photovoltaic production, electricity prices, merit order effect, energy mix.

1 INTRODUCTION

1.1 General statements on renewable energies

The EU member states have committed to a drastic increase of the share of renewable energy ("RE") sources in their energy mix. Renewables behave very differently from conventional sources in several ways, which requires each country to adapt its energy policy:

- Intermittency: RE production needs priority of dispatch because it can hardly be foreseen and electricity generated cannot be stored. This may also lead to an increased need for spare peak production capacities to be available to cope with the increased intermittency in the grid,
- Segmentation: most RE plants are small and widely distributed within a country, which requires grid reinforcement works,
- Although the cost of photovoltaic ("PV") modules has dramatically decreased over the past few years (from approx. 4 €/Wp to approximately 0.5 €/Wp), it seems to have reached a floor. The levelised cost of electricity (as defined below) produced from a PV plant remains higher than most other technologies. Therefore PV producers need monetary support: revenue schemes (FiT, ROCs, GC…), tax incentives, direct subsidies, etc.

1.2 Observed impacts of RE on electricity markets

The effects of RE generation on electricity markets are still unclear and certainly dependent on each country's energy mix. The latest quarterly report on European electricity markets [1] illustrates this conundrum as it has been observed that the injection of renewable energy production in the grid yields antagonist effects on market prices: "intermittent power generation sources, such as wind and solar, played an increasingly important role in the power mixes of many European countries during the second quarter of 2013. In Central Western and Central Eastern Europe, high levels of renewables generation contributed to the lowest wholesale power prices observed in the last few years. […] [However] Frequent occurrences of negative prices in many European markets signal the need for better integration of renewables into the power grid. On a Sunday afternoon in mid-June, wind and solar assured more than 60% of power generation in Germany, resulting in negative hourly prices in the whole Central Western Europe region."

1.3 Purpose of this study

The authors will opine neither on the adequacy or efficiency of a given support framework for RE, nor on the global cost or benefit of RE. The study aims at providing food for thoughts about the monetary impact of renewables for society. This requires to compare the costly consequences of the introduction of renewables in the energy mix (grid reinforcement, potentially additional peak capacity reserves to cope with increased intermittency, subsidies to renewables producers, times of overproduction leading to negative prices) to the gain generated by the downward pressure on market spot prices when renewables produce electricity.

The purpose of this study is to measure the benefit generated in Italy by the PV production over the past 7 years. Such analysis will be performed based on historical and statistical methods. The behavior of that benefit with respect to the penetration rate of PV within Italy's energy mix and with the correlation between PV production and electricity demand will also be assessed.

2 THE MERIT-ORDER EFFECT

2.1 Preliminary definitions and scope of work

Some elementary concepts need to be defined and distinguished before going forward:

- Cost of electricity
    a. The levelised cost of electricity ("LCOE") is the average cost of a megawatt hour ("MWh") produced by a given plant, including the fuels cost required to produce a MWh, but also the operating expenses (maintenance, taxes, …) as well as the amortization of the investment. The LCOE of PV plants was divided by more than

  five over the past years,
  b. The marginal cost of electricity represents at a given time, the cost to generate an additional MWh of electricity, e.g. only the cost of gas for a gas plant. By definition, the marginal cost for RE amounts to zero (no fuel cost).

- Price of electricity
  c. Retail prices paid by end consumers are set in long term fixed price contracts and include additional taxes,
  d. Wholesale prices (also referred to as market spot prices) are traded on electricity markets daily and will be the focus of this study,
  e. Price paid to electricity producers, which typically include the revenue support schemes for RE producers. This study does not focus on this metric.
- Net value for society
  f. It includes a monetary part (i.e. the total energy bill of the country), but also
  g. All sorts of non-monetary externalities (e.g. intermittency of renewable energy, fossil fuels depletion risks, energy security, dependency on unstable foreign countries, pollution, public health…),
  h. This study only focuses on monetary terms, and attempts to scrutinize if the injection of PV generation capacity into the grid lowers or increases the end consumers' energy bill at the scale of the whole country.
- Merit order effect ("MOE")
  i. The MOE is the downward pressure on prices exercised by RE sources when they feed electricity into the grid (detailed in section 2),
  j. In order to quantify that phenomenon, one must compare the historical payments for energy of the country over a certain period to what such payments would have been had there been no RE production. This requires to simulate what the prices of electricity would have been then (see section 3),
  k. This study proposes a method based on the fact that for a given country, in a sufficiently short time frame (typically a year), there is a direct relationship between instantaneous demand and electricity price.

2.2 Electricity markets

An electricity market is an exchange platform aggregating supply and demand for electricity.

- Demand for electricity is a short term phenomenon and can be considered inelastic to price because consumers are supplied on long term contracts. It was therefore assumed that the Italian demand profile over the study period would have been the same had the price been different.
- Supply : Typical energy mix can be split in three categories of energy sources:
  l. Base load, such as nuclear and conventional thermal power, to sustain a constant level of production. It is unable to adapt to short term variations in electricity demand. It typically has high fixed costs and low marginal costs,
  m. Peak load, such as gas, to adapt to high sudden demand. Units are usually smaller with low fixed costs and high marginal costs. These production facilities are utilized only a few hours per year but charge high prices because of the instantaneous shortage in supply, and
  n. Mid load in between such as coal or combined heat and power ("CHP").
- Electricity market prices : this study focuses on the prices observed on the day-ahead market (also referred to as the spot market) and not on the prices observed on other markets (such as the futures market for long term trades, the intraday market or the capacity reserve market)

As electricity cannot be stockpiled (except in some hydro installations, to a minor extent) there needs to be a perfect clearance at each time between demand for electricity and power injected in the grid. The grid regulator tries to forecast demand, and different available power plants will adapt to this forecasted output: power plants with the lowest marginal cost will be tapped in first.

In market environments, prices at a given time are thus determined by the most expensive power producers able to satisfy the demand (i.e. with the highest marginal costs) and are imposed on all other producers (since in a pure competitive market, equilibrium between supply and demand is met when price equals marginal cost).

In a perfectly competitive and transparent market, it is then possible to build the relationship between the electricity demand at a given time and the associated price by sorting energy sources in growing order of marginal cost. This step function is called the merit order curve ("MOC"). The width of each step represents the supply capacity of an energy source while its height is its marginal cost (see figure 1 below).

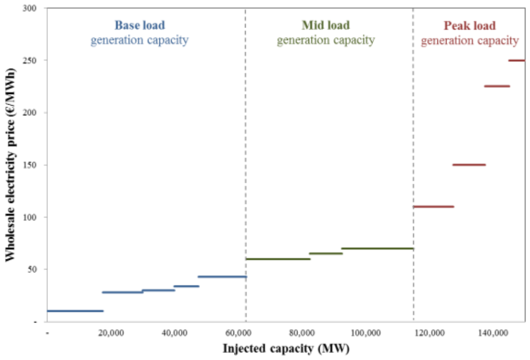


Figure 1: MOC of a fictive electricity market (source: authors)

Therefore, the electricity wholesale prices will be determined as the intersection of the instantaneous demand and the MOC, representing the marginal cost for a given production.

In the MOC context, the case of RE is unusual since they do not behave as a base, mid or peak power plant. As previously mentioned, power suppliers have to buy the renewable power injected in the network (due to the priority of RE production in the grid) and since electricity demand is inelastic in the short-term, any RE production will decrease demand for other power sources. Since the MOC has a positive slope, this translates into lower wholesale electricity prices. This is defined as the MOE and displayed in figure 2 below.

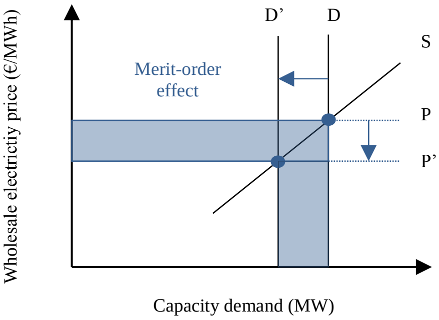


Figure 2: MOE of PV generation (source: authors)

This paper attempts to build the MOC and quantify the MOE for Italy between 2006 and 2012 (with technicalities detailed in next sections).

2.3 Set of assumptions and protocol of the study

The authors based their study on Italy because they estimated it is the European country that fits best with the following necessary criteria for the study.

Italy has experienced a massive growth of installed PV capacity over the past years, exceeding wind. It is thus possible to measure the MOE behavior with respect to the PV penetration rate. Still, the latter remains modest, so peak PV production rarely leads to important market distortions like negative prices as are observed in Germany. Intuitively, this underlines the fact that PV production does not replace base load production but rather mid or peak load production. The results provided in this study are not robust to negative prices (see section 3) but as stated, fortunately no negative wholesale prices were observed in Italy since the first PV production in 2006.

Up until recently there was no incentive for self-consumption and Italy's electrical network is less interconnected to neighboring countries than other important PV markets like Germany: in 2012 in Italy, exports were insignificant (when compared to electricity consumption) whereas imports amounted to around 10% of the total electricity consumption [2] (mainly from France and Switzerland so mainly in the form of respectively base load nuclear and hydro that can be either base or peak). Thus the authors deemed reasonable to assume that the internal electricity consumption in Italy accurately matches the total electricity demand for Italy's electricity (and consequently electricity production).

Only a portion of the total electricity production (and thus consumption) is traded on electricity markets: the relation between electricity spot prices is de facto not obvious. Since only market prices were available the authors had to assume that all the electricity consumed is traded on the day-ahead market. This is a heavy assumption but traded volumes in European day-ahead markets have increased significantly over the last years, fluctuating above 40% since 2010 and reaching 52% of total electricity consumption in Q1 2013 [1]. Such assumption can further be justified by the fact that the mechanics of the day-ahead market are, in the long run, internalised in all the other contracts (long term purchase agreements, futures market...).

Thanks to the conjunction of these assumptions it appears reasonable to assume that all electricity (and therefore solar) produced is fed into the grid and consumed (no self-consumption, no export or import). The Italian electricity market is considered as efficient (overall prices reflected through electricity market mechanisms) and shows a diverse energy mix which leads to a MOC that is easily extractable (contrary to e.g. France with a vast majority of nuclear and hydro power) and most importantly invariant. Any injection of PV production in the grid should, under such observations, be reflected into a right shift of the MOC, as displayed in figure 3 below, leading to an overall decrease in prices.

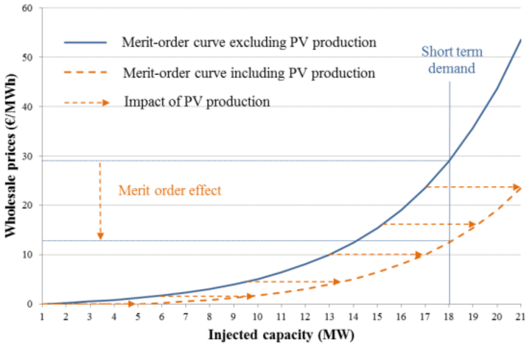


Figure 3: Impact of PV production on the MOC (source: authors)

As mentioned earlier (see definition of the MOE in section 2.1), in order to properly assess the impact of renewable electricity on market prices, the authors simulated what the wholesale price profile over the study period would have been had there been no PV generation. This implied intuiting certain properties of the MOC, i.e. of the relationship between wholesale prices and electricity consumption:

a. To circumvent the rightward shift that RE production leads on the MOC, the authors worked on the total consumption of electricity (equal to demand) retreated by the PV production in order to work in a referential with a fixed MOC.
b. If the time period is short enough, the MOC of a country does not vary materially. This assumes that gas and coal prices are not too volatile, and that the country's energy mix does not vary too much (new facilities built or old ones shut down) which is among the set assumptions made above for Italy,
c. It is intuited (and will be further tested) that the MOC has an exponential shape.

3 HISTORICAL ANALYSIS

3.1 MOC and MOE computation methodology

Hourly time series for PV production were reconstructed, between 2006 and 2012, from real solar irradiation data coupled with temperature data as follows:

- the solar irradiation profile was provided by GeoModel solar [3] for 16 sites in Italy (regional main cities), using data from the Meteosat Second Generation ("MSG") satellite in the original 15 minute step time series format,
- in order to achieve a harmonized data set for the whole study period, temperature (with its original time step of 1h/3h) was also resampled to a 15 minute step time series, and

- the irradiation data set was then transformed into a normalized production of PV plants using a specific performance ratio varying with temperature, and integrated into hourly values (based on the 15 minute time step profiles).

The final Italian PV production time series were obtained based on the hourly normalized PV production weighted by the hourly PV capacities in the Italian regions (which were linearly interpolated from the monthly PV capacities data provided by GSE [4]).

The Italian regions were grouped in three zones:

- the northern region comprises Emilia Romana, Friuli Venezia, Liguria, Lombardia, Piemonte, Toscana, Trentino, Valle d'Aoste and Veneto,
- the central region comprises Abruzzo, Lazio, Marche, Umbria and Sardegna (connected to the Lazio grid),
- the southern region which comprises Basilicata, Calabria, Campania, Molise, Puglia and Sicilia.

The hourly PV production series obtained are the closest achievable estimation of the real PV production.

The hourly time series for the total electricity consumption [5] and wholesale electricity prices [6] in Italy were extracted from public databases.

As mentioned in section 2 above, it was assumed that the MOC is invariant, and equivalently, that any PV production reduces demand for mid load and peak load generation sources. Based on the sets of values obtained previously, a MOC is obtained through a linear regression of the logarithm of wholesale prices (no negative wholesale prices were observed on the 2006 to 2012 period) on the total electricity consumption net of PV production for a given period of time. Should the estimates thus derived be statistically significant, the wholesale prices that would have been observed, during such period of time, for a theoretical electricity market without any PV generation capacity, can be simulated with the following formula (with a and b the results of the regression):

$$\begin{aligned} MOC : electricity\ consumption\ (c) &\rightarrow wholesale\ price\ (p) \\ c &\rightarrow e^{a+b*c} \end{aligned}$$

The MOE over a certain period of time is derived from the corresponding MOC as the difference, on the considered period of time, between the total electricity spending of a theoretical electricity market without PV power plants (using the MOC to simulate the theoretical wholesale electricity prices) and the actual spending for electricity consumed. The MOE is the additional amount that would have been spent for the same consumption profile but without PV generated electricity, or equivalently, the MOE represents the monetary gain induced by PV production over a period of time.

Normalized by the total electricity generated by PV power plants, it provides an order of magnitude of a bonus price that can remunerate the PV asset operators on top of the wholesale price. Such quantity is thereafter defined as the merit-order price (the "MOP").

$$MOE = \sum \left(p_{no\ pv,simulated} - p_{pv,observed} \right) * c_{observed}$$

$$MOP = MOE\ /\ Total\ PV\ production$$

3.2 Results for the historical analysis

The MOCs that were calculated for each year between 2006 and 2012 (dotted curves in figure 4 and results in table I below) as well as for the whole 2006-2012 period (plain curve in the figure 4 and results in table II below) display fairly significant correlations between wholesale prices and electricity consumption (R^2 factor above 70%), which validates the set of assumptions listed in section 2.3.

Overall, the above results tend to validate the assumption that the MOC has an exponential shape and does not vary much over time. For each MOC, a MOE and MOP were calculated (see tables below).

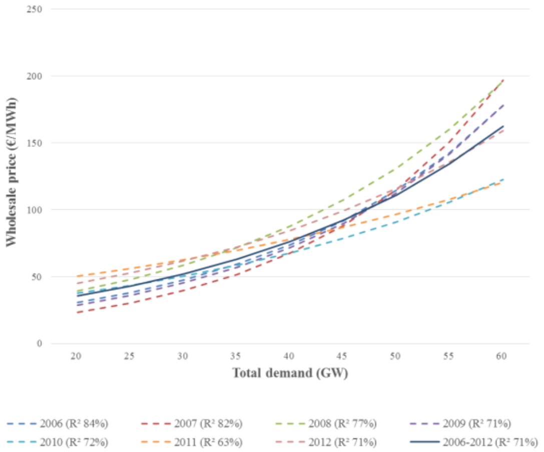


Figure 4: MOC for years from 2006 to 2012 and aggregated for the 2006-2012 period (source: authors' calculation)

Table I: MOC, MOE and MOP results for each year between 2006 and 2012, as well as for the whole 2006-2012 period (source: authors' calculation)

Years	a	**MOC** b	R²	**MOE** (€)	**MOP** (€/MWh)
2006	2.55	$4.39\ 10^{-5}$	84%	$4.18\ 10^{5}$	165.2
2007	2.08	$5.34\ 10^{-5}$	82%	$8.19\ 10^{6}$	201.7
2008	2.87	$4.02\ 10^{-5}$	77%	$3.42\ 10^{7}$	172.3
2009	2.46	$4.54\ 10^{-5}$	71%	$9.33\ 10^{7}$	134.4
2010	3.04	$2.95\ 10^{-5}$	72%	$1.57\ 10^{8}$	85.9
2011	3.48	$2.18\ 10^{-5}$	63%	$7.06\ 10^{8}$	64.2
2012	3.18	$3.15\ 10^{-5}$	71%	$1.90\ 10^{9}$	108.8
2006-12	2.82	$3.78\ 10^{-5}$	71%	$3.60\ 10^{9}$	115.2

Table II: MOC, MOE and MOP results with the 2006-2012 MOC applied to all other years (source: authors' calculation)

	Yearly MOCs		**2006-12 MOC**	
Years	**MOE** (€)	**MOP** (€/MWh)	**MOE** (€)	**MOP** (€/MWh)
2006	$4.18\ 10^{5}$	165.2	$3.60\ 10^{5}$	142.3
2007	$8.19\ 10^{6}$	201.7	$5.98\ 10^{6}$	147.3
2008	$3.42\ 10^{7}$	172.3	$2.77\ 10^{7}$	139.5
2009	$9.33\ 10^{7}$	134.4	$8.16\ 10^{7}$	117.6
2010	$1.57\ 10^{8}$	85.9	$2.31\ 10^{8}$	126.6
2011	$7.06\ 10^{9}$	64.2	$1.19\ 10^{9}$	108.1
2012	$1.90\ 10^{9}$	108.8	$2.07\ 10^{9}$	118.1
2006-12	$3.60\ 10^{9}$	115.2	$3.60\ 10^{9}$	115.2

As table I and figure 5 show, the MOE, of course, increases over time. They also show that the MOP remains surprisingly stable over the 7 years of observation, given the dramatic variation of PV installed capacity during these years.

It is to be noted that if the MOP were to be paid to PV plants as a bonus on top of the market price for every MWh of PV produced, the total tariff received would be close to 200 €/MWh, i.e. above the current feed-in-tariff offered in EU countries.

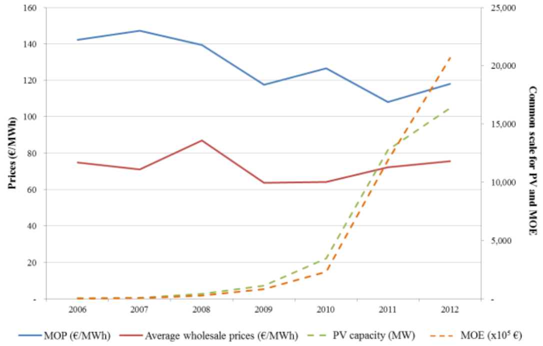


Figure 5: MOP (based on the 2006-12 MOC), average wholesale prices, MOE (based on the 2006-12 MOC) and PV capacities installed between 2006 and 2012 (source: authors' calculation)

The MOP calculated above shows a downward trend with quite some variability. A first interpretation could be that the MOE is less efficient as the PV penetration rate increases. In reality, only seven years of history is too short to validate any theory on which driver may affect the MOE. Such drivers could be the correlation between the solar irradiation and consumption profiles or the PV penetration rate.

In order to have a more reliable answer, the authors adopted a statistical analysis to observe the MOE variations with a large number of irradiation profiles, with different electricity demand profiles and different shares of installed PV capacity.

For the sake of consistency, and to allow an adequate comparison between the various metrics detailed section 4, the remainder of the study assumed that the MOC is the one obtained for the 2006 to 2012 period.

4 STATISTICAL ANALYSIS

4.1 Statistical average merit-order effect computation

Seven years of historical data is obviously too short to assess with a high level of reliability the MOE at the scale of a country. Policy makers and economic agents may have an interest in predicting its value for the years to come as it will impact the forward prices and may influence their decisions. The MOE is by definition dependant on the PV production profile and how it correlates with the consumptions profile. A statistical approach is thus proposed, in order to observe how the MOE behaves with respect to different PV production profiles.

The data used for this section are the hourly PV production profiles (MWh) and the hourly installed PV capacity (MWp) between 2006 and 2012, to obtain hourly profiles (i.e. the ratio of the PV production by the installed PV capacity (MWh/MWp)).

A Monte Carlo simulation was run on a central hourly yield profile over a year. Each hourly yield was modelled as an independent random variable following a normal law (there are therefore 8760 Gaussian random yield variable). Each hourly yield has 7 samples (for 2006 to 2012), from which the authors have calculated an average and a standard deviation.

The Monte Carlo simulation was run 100 times (on each of the 8760 random yields just defined), leading to 100 random yearly yield profiles. The authors then calculated 100 PV production profiles for each of the 7 years of historical PV installation capacities in the country. The authors could also calculate 100 profiles of demand retreated by PV production for each of the 7 years of historical demand profiles, leading to 49 combinations.

For each of these 49 combinations, 100 values of the MOE and MOP were calculated, using the MOC calculated between 2006 and 2012. The authors used the same MOC throughout the combinations in order to have a common basis for comparison. A statistically meaningful average of the MOE and the MOP were then calculated for each combination.

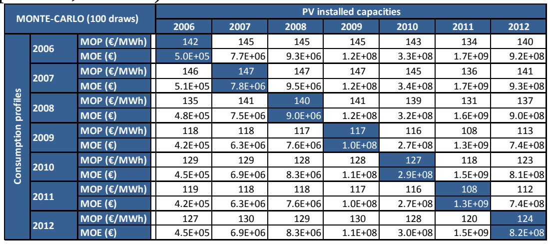
4.2 Results

The results tables should be read as follows:

- along columns the amount of installed PV capacities varies (from 2006 to 2012)
- along rows the profile of total electricity demand varies as observed from 2006 to 2012.

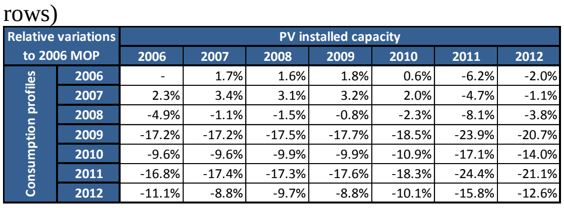
Hence the diagonal values show a more reliable (because more statistically meaningful) estimate of the MOE and the MOP of the given year. Note for instance that the MOP are almost identical to the ones on the last column of table II (with a 1% tolerance).

Table III: MOP and MOE varying with the PV penetration rate (installed capacity, in columns) and with electricity demand profiles (i.e. with the PV irradiation profiles, in rows)



MONTE-CARLO (100 draws)			PV installed capacities						
			2006	2007	2008	2009	2010	2011	2012
Consumption profiles	2006	MOP (€/MWh)	142	145	145	145	143	134	140
		MOE (€)	5.0E+05	7.7E+06	9.3E+06	1.2E+08	3.3E+08	1.7E+09	9.2E+08
	2007	MOP (€/MWh)	146	147	147	147	145	136	141
		MOE (€)	5.1E+05	7.8E+06	9.5E+06	1.2E+08	3.4E+08	1.7E+09	9.3E+08
	2008	MOP (€/MWh)	135	141	140	141	139	131	137
		MOE (€)	4.8E+05	7.5E+06	9.0E+06	1.2E+08	3.2E+08	1.6E+09	9.0E+08
	2009	MOP (€/MWh)	118	118	117	117	116	108	113
		MOE (€)	4.2E+05	6.3E+06	7.6E+06	1.0E+08	2.7E+08	1.3E+09	7.4E+08
	2010	MOP (€/MWh)	129	129	128	128	127	118	123
		MOE (€)	4.5E+05	6.9E+06	8.3E+06	1.1E+08	2.9E+08	1.5E+09	8.1E+08
	2011	MOP (€/MWh)	119	118	118	117	116	108	112
		MOE (€)	4.2E+05	6.3E+06	7.6E+06	1.0E+08	2.7E+08	1.3E+09	7.4E+08
	2012	MOP (€/MWh)	127	130	129	130	128	120	124
		MOE (€)	4.5E+05	6.9E+06	8.3E+06	1.1E+08	3.0E+08	1.5E+09	8.2E+08

Table IV: relative variations of the MOP compared to the 2006 value (142 €/MWh) with the PV penetration rate (installed capacity, in columns) and with electricity demand profiles (i.e. with the PV irradiation profiles, in rows)



Relative variations to 2006 MOP		PV installed capacity						
		2006	2007	2008	2009	2010	2011	2012
Consumption profiles	2006	-	1.7%	1.6%	1.8%	0.6%	-6.2%	-2.0%
	2007	2.3%	3.4%	3.1%	3.2%	2.0%	-4.7%	-1.1%
	2008	-4.9%	-1.1%	-1.5%	-0.8%	-2.3%	-8.1%	-3.8%
	2009	-17.2%	-17.2%	-17.5%	-17.7%	-18.5%	-23.9%	-20.7%
	2010	-9.6%	-9.6%	-9.9%	-9.9%	-10.9%	-17.1%	-14.0%
	2011	-16.8%	-17.4%	-17.3%	-17.6%	-18.3%	-24.4%	-21.1%
	2012	-11.1%	-8.8%	-9.7%	-8.8%	-10.1%	-15.8%	-12.6%

As displayed in the tables above, the MOP varies much more along columns than along rows. This indicates that the MOP does not depend much on the penetration rate of PV in the country's energy mix (total PV capacity installed), but rather varies significantly with the electricity demand profile, or to be precise, with the correlation between demand and PV production during the year.

5 CONCLUSION

This study aimed at quantifying the savings incurred at the country level in Italy over the past 7 years as a result of the decrease in electricity spot market prices observed when PV plants feed electricity into the grid.

The authors showed that the total electricity demand retreated by PV production is well correlated to the prices, following an exponential curve (R^2 above 70%). That good correlation proves that the strong set of assumptions was acceptable (no export or import, no self-consumption, all electricity demand traded on the spot market, stable energy mix and price behaviour).

The MOE, i.e. the aggregated energy bill saving in a year, has of course increased as more PV plants were installed, reaching a circa. € 2 Bn amount in 2012. If such benefit could be monetised by the public authorities, it could be invested in infrastructures that are necessary to be built because of the introduction of renewables in the energy mix such as grid reinforcement works or in spare peak capacities to allow peak producers to remain profitable.

The MOP (MOE expressed per MWh of PV production) has remained above 100 €/MWh, which could be paid as a bonus to PV producers on top of their sale on the spot market.

A statistical approach enabled the authors to simulate a large number of PV production profiles, and calculate the MOP with 7 different electricity demand profiles and 7 penetration rates. The results obtained showed to be fairly close to the 7 original observations. The statistical analysis revealed that the MOP does not depend much on the penetration rate of PV, but is quite dependant on the particular electricity demand profile, and therefore on how well it is correlated to the PV production profile.

This paper opens the route for further improvements, including:

- calculate the MOE induced by wind;
- take account of export/import and self-consumption;
- run the Monte Carlo on irradiation (which is expected to follow more closely a Gaussian behaviour) rather than yield; and
- calculate the MOE for other European countries.

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