QUANTITATIVE ANALYSIS OF THE MERIT ORDER EFFECT FROM PHOTOVOLTAIC PRODUCTION IN KEY EUROPEAN COUNTRIES

Henri GOUZERH (Green Giraffe Energy Bankers, 8 rue d'Uzès 75002 Paris, h.gouzerh@green-giraffe.eu),
Sinead ORLANDI (European Photovoltaic Industry Association, 63-67 Rue d'Arlon-1040 Brussels, s.orlandi@epia.org),
Nicolas GOURVITCH (Green Giraffe Energy Bankers, 8 rue d'Uzès 75002 Paris, n.gourvitch@green-giraffe.eu), and
Gaëtan MASSON (European Photovoltaic Industry Association, 63-67 Rue d'Arlon-1040 Brussels, g.masson@epia.org)

ABSTRACT: This study builds on a 2013 paper from M.Gourvitch, M.Gouzerh, M.Carton and M.Masson on "Quantitative analysis of the merit order effect from photovoltaic production in Italy". This study proposes a method to quantify the savings incurred by the end consumers in a set of European countries over the past 8 years as a result of the decrease in electricity spot market prices observed when PV plants feed electricity into the grid. The 2013 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. This study will research whether the same effect can be seen in other European countries, France, Germany, Austria and Switzerland. 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 gets close to 100 €/MWh, and has exceeded € 20 Bn at the country scale over the past 7 years. Also, average wholesale prices would have been 3% (or 1.5 €/MWh) higher had there been no PV production. 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. Last year's 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. 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 by the PV production over the past 8 years in Germany, Austria, France, Switzerland and Italy ("GAFSI"). 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 GAFSI'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 wholesale spot market prices) are traded on electricity markets daily and will be the focus of this study, i.e. the authors will not tackle prices observed on other markets (such as the futures market for long term trades, the intraday market or the capacity reserve market),
    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 was considered inelastic to price in the study because most 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.
- Market coupling: power markets in Europe are currently not integrated with other countries' electricity markets. Their organization at national level can have an impact on the electricity prices since renewables can affect the demand profile generating downward pressure on prices when they feed electricity into the grid. Thanks to a market coupling the energy produced by PV could be counterbalanced between countries in order to be able to manage the electricity prices according to the different country demand profiles. As the study is made at GAFSI level rather than on a per country basis, the authors have opted to focus on the weighted average price ("WAP") of the market prices observed in each country by their respective overall electricity consumption (see section 2.3).

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. Each supplier estimates their demand profile and purchases electricity accordingly: therefore power plants with the lowest marginal cost will be tapped in first. The system operator is ultimately responsible to guarantee security and adequacy of supply but will settle mismatches between supply and demand on a bilateral basis with balancing costs..

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 purely competitive market, equilibrium between supply and demand is met when price equals marginal cost). This "uniform pricing" principle is the case in most markets, but there are indeed some markets with "pay-as-bid" clearance.

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).

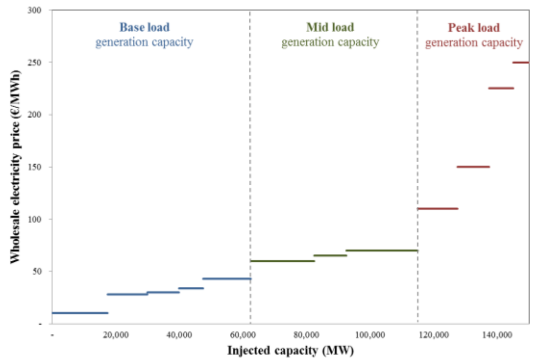

Figure 1: MOC of a fictive electricity market (source: authors)

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 always purchase the renewable power injected in the network (due to the priority of RE production in the grid and because renewables always align to the lowest price) 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.

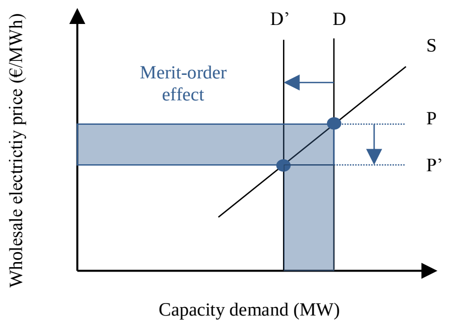

Figure 2: MOE of PV generation (source: authors)

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 the GAFSI because they estimated it is the set of European country that fits best with the following necessary criteria for the study.

GAFSI has experienced a massive growth of installed PV capacity over the past years. It is thus possible to measure the MOE behavior with respect to the PV penetration rate. Still, at the GAFSI scale the latter remains modest (about 3%), so peak PV production does not lead to important market distortions on a recurrent basis like negative prices as are observed in Germany alone. Intuitively, this underlines the fact that PV production does not replace base load production but rather mid or peak load production (again at the GAFSI level). The results provided in this study are not robust to negative prices (see section 3) but as stated, fortunately less than 0.1% of negative AWP were observed at the GAFSI level between 2006 and 2013 (less than 0.3% in Germany alone, and none in Italy and Switzerland).

Up until recently there was little incentive for self-consumption in most GAFSI countries (especially in Germany) and most electricity imports and exports occur within the GAFSI countries: in 2013, exports to and imports (respectively net export) from GAFSI were insignificant compared to the overall internal electricity production, about 6% (respectively 1% in [2]). Taken individually, the countries composing GAFSI show significantly higher shares of imports and exports to production: France alone is the biggest electricity exporter in Europe, mainly to Switzerland (30%) and Italy (21%), and the vast majority of its imports are from Germany (47%) and Switzerland (23%) [3] hence the rationale for studying the GAFSI system and internalize the vast majority of inter-country electricity trades.

The authors thus deemed reasonable to assume that the internal electricity consumption in GAFSI accurately matches the total electricity demand for GAFSI'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 GAFSI 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 alone 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.

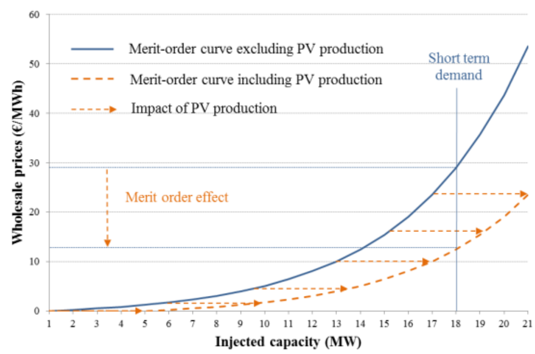

Figure 3: Impact of PV production on the MOC (source: authors)

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 GAFSI,
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 2013, from real solar irradiation data coupled with temperature data as follows:

- the solar irradiation profile was provided by GeoModel solar [4] for 60 regions/cities within GAFSI (regional main cities), using data from the Meteosat Second Generation ("MSG") satellite in the original 15 minute or hourly 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 or hourly 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 or hourly time step profiles).

The final GAFSI PV production time series were obtained based on the hourly normalized PV production weighted by the hourly PV capacities in the GAFSI regions (which were linearly interpolated from the monthly PV capacities data provided by GSE [5]).

The GAFSI regions were grouped in 60 zones:

- Germany: 16 regions
- Austria: considered as one region
- France: 22 regions (including Corsica)
- Switzerland : considered as one region
- Italy: 20 regions.

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 [6] and wholesale electricity prices [7] 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 (outliers - negative wholesale prices – are insignificant and have been disregarded) 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):

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

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").

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

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

3.2 Results for the historical analysis

The MOCs have first been estimated on a country per country basis but the correlation factors proved to be quite poor: Germany alone showed about 57%. Adding Austria, France, Switzerland and Italy, the biggest trading partners of Germany allowed to increase the correlation factor to about 70% as showed below, comforting the assumption that external trades do have a non-negligible impact on the MOE estimation.

The MOCs that were calculated for each year between 2007 and 2013 (dotted curves in figure 4 and results in table I below) as well as for the whole 2007-2013 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).

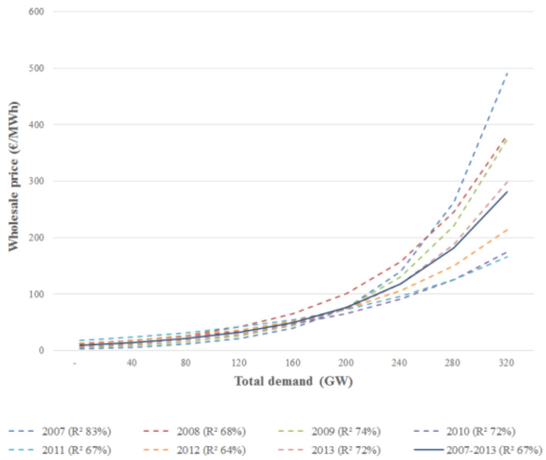

Figure 4: MOC for years from 2007 to 2013 and aggregated for the 2007-2013 period (source: authors' calculation)

Table I: MOC, MOE and MOP results for each year between 2007 and 2013, as well as for the whole 2007-2013 period (source: authors' calculation)

	MOC			MOE	MOP
Years	a	b	R²	(€)	(€/MWh)
2007	1.19	$1.56\ 10^{-5}$	83%	$0.5\ 10^{9}$	137
2008	2.42	$1.10\ 10^{-5}$	68%	$0.9\ 10^{9}$	148
2009	1.71	$1.32\ 10^{-5}$	74%	$1.0\ 10^{9}$	108
2010	2.56	$8.13\ 10^{-6}$	72%	$1.2\ 10^{9}$	73
2011	2.91	$6.89\ 10^{-6}$	67%	$2.4\ 10^{9}$	67
2012	2.55	$8.81\ 10^{-6}$	64%	$4.6\ 10^{9}$	84
2013	2.00	$1.16\ 10^{-5}$	72%	$5.9\ 10^{9}$	97
2007-13	2.18	$1.08\ 10^{-5}$	67%	$19.0\ 10^{9}$	100

Table II: MOC, MOE and MOP results with the 2007-2013 MOC applied to all other years (source: authors' calculation)

	Yearly MOCs		2006-12 MOC	
	MOE	**MOP**	**MOE**	**MOP**
Years	(€)	(€/MWh)	(€)	(€/MWh)
2007	$0.5\ 10^{9}$	137	$0.4\ 10^{9}$	108
2008	$0.9\ 10^{9}$	148	$0.6\ 10^{9}$	110
2009	$1.0\ 10^{9}$	108	$0.9\ 10^{9}$	95
2010	$1.2\ 10^{9}$	73	$1.7\ 10^{9}$	106
2011	$2.4\ 10^{9}$	67	$3.5\ 10^{9}$	100
2012	$4.6\ 10^{9}$	84	$5.5\ 10^{9}$	100
2013	$5.9\ 10^{9}$	97	$5.8\ 10^{9}$	96
2007-13	$19.0\ 10^{9}$	100	$19.0\ 10^{9}$	100

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 150 €/MWh, as the average WAP is close to 50 €/MWh, which is in the range of the current feed-in-tariff offered in EU countries.

Equivalently, the average market price would have been 3% higher (1.5 €/MWh) had there been no PV generation between 2007 and 2013, as shown in table III below.

Table III: Average market price reduction between 2007 and 2013 (based on the 2007-13 MOC)

	Average WAP		Price reduction	
	Excl. PV	**Incl.PV**		
Years	(€/MWh)	(€/MWh)	(€/MWh)	(%)
2007	53.3	53.0	0.3	0.5%
2008	53.6	53.2	0.4	0.8%
2009	49.7	49.1	0.6	1.2%
2010	54.6	53.5	1.1	2.0%
2011	52.3	50.0	2.3	4.4%
2012	52.2	48.7	3.5	6.7%
2013	51.7	47.9	3.8	7.3%
2007-13	52.5	51.0	1.5	2.9%

Those results are in line with what other research such as Frank Sensfuß, Mario Ragwitz and Massimo Genoese (2008) [8].

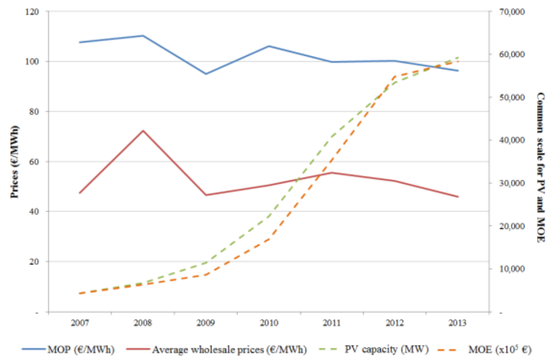

Figure 5: MOP (based on the 2007-13 MOC), average wholesale prices, MOE (based on the 2007-13 MOC) and PV capacities installed between 2007 and 2013 (source: authors' calculation)

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 2007 to 2013 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 2013, to obtain hourly profiles (i.e. the ratio of the PV production by the installed PV capacity (MWh/MWp)). There is one additional year (2006) compared to the previous section as the authors did not have access to the wholesale prices for that year to run the historical calculations.

A Monte Carlo simulation was run on a central hourly yield profile over a year. Each hourly yield for each of the main 60 regions of GAFSI (see section 3.1) was modelled as an independent random variable following a normal law (there are therefore 8760 Gaussian random yield variable). Each hourly yield has 8 samples (for 2006 to 2013), 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) for each of the 60 main GAFSI cities, leading to 6000 random yearly yield profiles. The authors then calculated 100 PV production profiles for each of the 8 years of historical PV installation capacities (2006-2013) around the 60 main GAFSI cities (hence a total of 6000 PV production profiles). The authors could also calculate 100 profiles of demand in GAFSI retreated by PV production for each of the 8 years of historical demand profiles, leading to 64 combinations.

For each of these 64 combinations, 100 values of the MOE and MOP were calculated, using the MOC calculated between 2007 and 2013. 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 2013)
- along rows the profile of total electricity demand varies as observed from 2006 to 2013.

Diagonal values show a more reliable (statistically meaningful) estimate of the MOE and MOP for a given year (note that the MOP are almost identical to the ones on the last column of table II, with a 2% tolerance).

Table IV: 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	2013
Consumption profiles	2006	MOP (€/MWh)	108	107	107	107	105	101	99	98
		MOE (€)	2.8E+08	4.1E+08	6.3E+08	1.0E+09	1.8E+09	3.7E+09	5.6E+09	6.6E+09
	2007	MOP (€/MWh)	111	110	110	110	108	105	101	100
		MOE (€)	2.9E+08	4.2E+08	6.4E+08	1.0E+09	1.9E+09	3.8E+09	5.8E+09	6.8E+09
	2008	MOP (€/MWh)	112	112	112	112	109	106	103	101
		MOE (€)	3.0E+08	4.3E+08	6.5E+08	1.0E+09	1.9E+09	3.9E+09	5.9E+09	6.9E+09
	2009	MOP (€/MWh)	98	97	97	97	95	92	90	88
		MOE (€)	2.6E+08	3.7E+08	5.7E+08	9.1E+08	1.6E+09	3.4E+09	5.1E+09	6.0E+09
	2010	MOP (€/MWh)	110	110	110	110	108	104	101	100
		MOE (€)	2.9E+08	4.2E+08	6.4E+08	1.0E+09	1.9E+09	3.8E+09	5.8E+09	6.8E+09
	2011	MOP (€/MWh)	106	106	106	105	103	100	97	96
		MOE (€)	2.8E+08	4.1E+08	6.2E+08	9.9E+08	1.8E+09	3.6E+09	5.6E+09	6.5E+09
	2012	MOP (€/MWh)	108	108	107	107	105	102	99	98
		MOE (€)	2.9E+08	4.2E+08	6.3E+08	1.0E+09	1.8E+09	3.7E+09	5.7E+09	6.6E+09
	2013	MOP (€/MWh)	106	106	106	106	104	100	98	96
		MOE (€)	2.8E+08	4.1E+08	6.2E+08	9.9E+08	1.8E+09	3.6E+09	5.6E+09	6.5E+09

Table V: relative variations of the MOP compared to the 2006 value (108 €/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								Maximum variation
		2006	2007	2008	2009	2010	2011	2012	2013	
Consumption profiles	2006	-	-0.3%	-0.6%	-0.6%	-2.6%	-5.9%	-8.1%	-9.3%	*9.3%*
	2007	2.7%	2.4%	2.2%	2.0%	0.6%	-2.8%	-5.8%	-7.4%	*10.1%*
	2008	4.4%	4.1%	3.8%	3.5%	1.6%	-1.9%	-4.6%	-6.0%	*10.4%*
	2009	-9.5%	-9.7%	-9.9%	-10.0%	-11.5%	-14.6%	-16.9%	-18.1%	*8.7%*
	2010	2.1%	2.1%	1.7%	1.8%	0.2%	-3.3%	-5.9%	-7.4%	*9.5%*
	2011	-1.5%	-1.7%	-2.0%	-2.1%	-4.0%	-7.3%	-9.6%	-10.9%	*9.4%*
	2012	0.3%	0.1%	-0.3%	-0.3%	-2.4%	-5.7%	-7.9%	-9.2%	*9.5%*
	2013	-1.2%	-1.6%	-1.8%	-1.9%	-3.9%	-7.2%	-9.5%	-10.6%	*9.4%*
Maximum variation		*13.9%*	*13.8%*	*13.7%*	*13.6%*	*13.1%*	*12.6%*	*12.3%*	*12.2%*	

As displayed in the tables above, the MOP varies 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.

This is however eased in the latest years 2011-2013 during which the penetration rate seems to be increasingly impacting in the variation of the MOP. As shown in the figure 6 below, the variance of the MOP with the PV penetration rate (the years on the x-axis correspond to a given capacity profile, i.e to columns in the table above): as more capacity is installed, PV production is ensured to supply a larger portion of the electricity demand from consumers. This could suggest that PV is starting to eat up base load capacity.

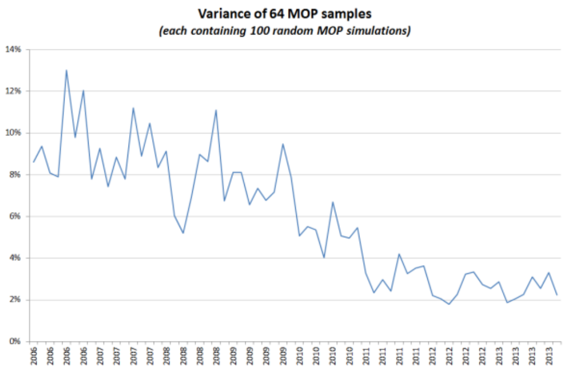

Figure 6: Variance of the 100 random MOPs for each of the 64 combinations (source: authors' calculation). On the x-axis the years are ordered between 2006 and 2013, and each year has 8 combinations (one per electricity demand profile)

5 SOCIAL BENEFITS: ARE WHOLESALE PRICES ACTUALLY DECREASING?

It has been estimated in sections 3 and 4 that (i) the MOP is close to 100 €/MWh and could be paid to PV plants as a bonus on top of the market price for every MWh of PV produced, and (ii) that the average market price would have been 3% higher (1.5 €/MWh) had there been no PV generation between 2007 and 2013.

In order to estimate the net social gains for society, several factors must be also taken into account such as the costs of the various support schemes to PV (tax incentives, feed-in tariffs) on the one hand, and, indirect gains through taxes, job creations and reduction of negative externalities (pollution, energy dependent on

Russian gas) on the other hand. As stated before, this is not the purpose of this paper.

However, it is possible to verify if the MOE is reflected in market prices throughout the years in the GAFSI countries (the authors are here referring to the presentation made by Francesco de Mango during the EUPVSEC 2013 conference [9]). In Germany, Austria, France and Switzerland, prices at night are lower than price during daytime and most importantly, prices tend to vary as per the electricity demand (see figure 7 below). In Italy however, it can be observed that starting from 2012, night time prices tend to de-correlate from electricity demand and rise above daytime price on average. This market anomaly should be further investigated.

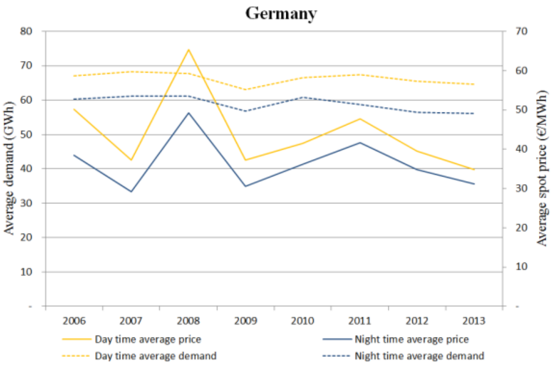

Figure 7: Average wholesale prices and electricity demand during day and night time in Germany

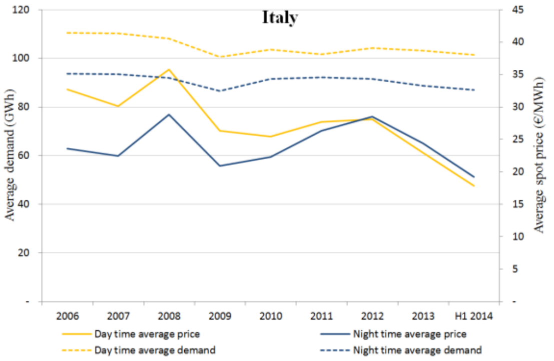

Figure 8: Average wholesale prices and electricity demand during day and night time in Italy

6 CONCLUSION

This study aimed at quantifying the savings incurred at the country level in Germany, Austria, France, Switzerland and Italy as a whole 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 around 70%). That good correlation proves that the strong set of assumptions was acceptable (low share of electricity export or import to production, 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. € 20 Bn amount in 2013. 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) is close to100 €/MWh, which could be paid as a bonus to PV producers on top of their sale on the spot market. Also, market prices would have been 3% higher (1.5 €/MWh) had there been no PV production.

A statistical approach enabled the authors to simulate a large number of PV production profiles, and calculate the MOP with 8 different electricity demand profiles (those observed between 2006- 2013) and 8 penetration rates (PV capacity installed between 2006-2013). The results obtained showed to be fairly close to the original observations. The statistical analysis revealed that the MOP is quite dependant on the particular electricity demand profile, and therefore on how well it is correlated to the PV production profile. Since 2011, the penetration rate of PV is also a significant explanatory variable, suggesting that PV could be replacing base load capacity.

Ultimately it has been observed that the negative pressure of PV production on wholesale prices is well reflected in Germany, Austria, France and Switzerland but some market anomalies are observed for prices during night time in Italy and should be further analysed.

Another contribution of this analysis is the quantitative assessment of the market coupling effect on PV impact on the electricity markets (through WAP). The same methodology could be applied to wind energy. In fact, as PV, it also represents a good share of the power generation of the countries analysed here. Further studies could sign the pathway to an integrated electricity market which will not only exploit the negative pressure of PV on electricity market but also what are at the moment known as weaknesses of the RE (i.e. intermittency).

This paper opens the route for other improvements:

- 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.

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