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The Impact of Solar Penetration on Solar and Gas Market Value: an application to the Italian Power Market

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Abstract

We assess the impact of solar penetration in the Italian wholesale electricity market on the market value of solar with respect to gas sources, measured as the ratio between the relative price they respectively earn and the average daily electricity price (value factor). We find that, on average, an increase of solar generation has a negative impact on the price earned by solar producers, thus causing a marginal departure from the grid parity condition. The relation between solar production and its market value is not constant over the years, while it depends on the degree of solar penetration. It is positive for very low levels of solar production while, as production increases, its marginal impact on the solar market value decreases and eventually becomes negative. An opposite relation is found when looking at the Gas market value. As solar displaces gas mainly during the peak-price hours, an initial solar penetration reduces the gas market value. However, as the solar share further increases, gas producers adapt their biding strategies. They switch production from the peak to the off-peak hours, where they exploit their temporary market power to increase the off-peak price. As a result, the relative price earned by gas producers is higher than the average daily price, increasing their market value with respect to renewable sources.

JEL Classification: C22; D40; Q41; Q42.

Keywords: Renewable sources, grid parity, solar, gas, Italian power market, electricity price, value factor

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1. Introduction

The increase of renewable energy sources (RES) constitutes one of the pillars of the European Climate and Energy Strategy. By 2020 at least 20% of the final energy consumption will have to be covered by RES (Directive2009/28/EC); at the same time, since RES have not reached the grid parity yet, various EU Member States have designed RES supporting schemes to achieve the 2020 RES target. By granting an economic return above the market price, these supporting schemes have promoted RES development in several European electricity markets. However, being passed through to the final electricity price, they imply a transfer from energy consumers to energy producers, raising a wide redistributive concern.

Against this background, several papers have analyzed the impact of RES development on consumers' welfare. A widely agreed result is that RES penetration reduces the daily average wholesale electricity price – a phenomenon known as *merit order effect* (Jensen and Skytte 2002, Ray et al. 2010) – thus partly offsetting the increase of the final electricity bill (Sensfuss et al. 2008, Moreno et al. 2012).

By lowering the wholesale electricity price, RES development not only affects consumers' welfare; it impacts the economic returns of power generators as well. This topic constitutes the core of our analysis. The goal of this paper is to assess how RES penetration affects the economic revenues and the market value of renewable sources with respect to traditional fossil fuels. Looking at the side of the economic returns, we aim at assessing whether an increase of RES generation has a negative impact on the price earned by RES producers, thus making it more difficult to achieve grid parity in the absence of any economic incentive. While public supporting schemes make RES more attractive, insofar a marginal increase of power generation from renewable sources reduces the electricity price that RES perceive, it is also likely to decrease marginally their economic returns. Under this perspective, further RES penetration may be associated with a marginal departure from the grid parity condition, thus affecting negatively the RES economic sustainability once public supporting schemes expire. Moreover, we analyze how RES penetration indirectly impacts the market bidding strategies of traditional operators and their respective revenues.

We develop a quantitative analysis to assess whether, and to which extent, the increase in the RES share in the energy mix affects differentially the daily electricity price with respect to the relative price earned by RES and traditional sources' power generators. In fact, being both electricity price and the power energy mix not uniformly distributed across the 24 daily hours, it is likely that the impact of RES growth on the daily average electricity price – which has been extensively analyzed to assess how RES penetration affects consumers' welfare – differs with respect to its impact on the relative price that renewable and traditional sources respectively earn when they produce[1]. To catch this differential impact, we measure the market value of RES and traditional sources as the ratio between the relative price they earn when selling electricity power exchange and the daily average electricity price: an index known as Value Factor (VF) (Lamont 2008, Mills and Wiser 2012, Hirth 2012). The VF indicates if the production-weighted price earned by each technology (unit revenues) is higher or lower than the daily market price, thus if such a technology has a market value higher or lower than average.

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[1] Since photovoltaic (PV) power generation is highly concentrated during the daytime, it is likely that solar penetration impacts on its relative price in a different way with respect to its impact on the daily average electricity price.

We apply our analysis to the Italian wholesale electricity market and, in particular, we focus on photovoltaic (PV) and gas sources. While gas represents the most important energy source in the Italian power mix, thanks to the feed-in premium called "*Conto Energia*" Italy has experienced the highest increase of PV installed capacity and production in the world (EPIA 2012, IEA 2013). We elaborate hourly data of price and power generation from PV and gas in the Italian wholesale electricity market to calculate their respective daily VF over the period 2007-2013[2]. After analyzing the trend of the VF and unit revenues for both PV and gas sources, we assess empirically how a variation of the PV share impacts on the solar and gas VFs. While avoiding the problem of excess noise that may arise when using hourly data, such an index allows us to assess whether the impact of RES penetration on the electricity price is uniform during the day of if rather it varies across the 24 daily hours. Being solar power generation highly concentrated during the daytime, the solar VF will be higher than 1 only if the peak price is higher than the daily average price, while it will decrease and become lower than 1 if RES penetration reduces the peak price to the extent that it becomes lower than the daily average price. This implies disentangling the direct impact of RES penetration on the wholesale electricity price when RES are available and drive traditional sources out from the market, from the trend of the electricity price when RES are absent from the market and traditional sources can bid strategically.

Moreover, as the PV share varies depending on both PV power generation and electricity demand, we disentangle the differential impact on PV power generation and energy consumption on the solar and gas VFs and unit revenues. The analysis is first developed over the period 2007-2013. Moreover, we replicate our analysis model year by year to assess whether the impact of PV power generation on the solar and gas VFs and unit revenues varies over time, depending on changes on the level of demand and on the amount of RES installed capacity.

We find that a marginal increase in solar production lowers the solar marginal revenues more than the gas ones. On the one hand, the increase in solar generation reduces the electricity price in the hours when solar generation is highly concentrated, thus lowering the relative price earned by solar producers. On the other hand, gas producers adapt their bidding strategies. They switch production from the peak to the off-peak hours – when solar is out from the market –, where they exploit their temporary market power and increase the off-peak price. Being the relative price earned by gas producers higher than the one earned by solar producers, solar penetration is associated with a reduction of the solar VF against an increase of the gas VF.

The paper is structured as follows. After this introduction, section 2 reviews the related literature on renewable energy. Section 3 presents, from a descriptive point of view, some trends in the Italian electricity market, section 4 introduces the concepts of economic returns and market value that the empirical analysis focuses on. Section 5 presents the empirical approach and the dataset and section 6 reports the results of the econometric analysis. Section 7 offers and interpretation of the results in line with broader development in the Italian energy market and the related theory, and Section 8 concludes.

[2] Data were available from January 2005 up to October 2013. Nevertheless, though the Italian power exchange was launched in 2005, we choose this period because before 2007 power generation by PV was negligible.

2. Related literature

The impact of RES development on the electricity market, and on the electricity price in particular, has gained increasing attention in the literature. Jensen and Skytte (2002) analyze the *merit order effect* on a theoretical basis. They point out that RES generation enters at the base of the merit order function, thus shifting the supply curve to the right and crowding the most expensive marginal plants out from the market, with a reduction of the wholesale clearing electricity price. More recently, several papers have quantified the impact of RES in different electricity markets, finding evidence of the merit-order effect. A first strand of this literature focuses on consumers' welfare and has analyzed how a variation of RES generation impacts on the daily average electricity price that consumers pay. Gelabert el al. (2011) find that an increase of renewable electricity production by 1 GWh reduces the daily average of the Spanish electricity price by 2 €/MWh. Wurzburg et al. (2013) focus on the German and Austrian integrated markets and find that additional RES generation by 1 GWh reduces the daily average price by roughly 1 €/MWh and. Both papers find that the electricity price reduction induced by higher RES production offsets the increase of retail price induced by the RES support scheme, thus increasing the consumers' surplus. Similarly, against the wide argument that Spanish feed-in tariffs represent an excessive cost to end users, Pereira and Saraiva (2013) apply a System Dynamics base model to the Iberian power market, assessing how wind power is likely to reduce the electricity price in the long run.

Rather than focusing on consumers' welfare, a second strand of literature analyzes the impact of RES supporting schemes on RES deployment towards grid cost parity. Along this line, Smith and Urpelainen (2014) demonstrate that the feed-in tariff represents an effective instrument to increase renewable electricity generation. Johnstone et al. (2010) find that RES supporting schemes play a significant role in promoting innovation in the field of renewable energy. Various papers argue that, by stimulating innovation and diffusion of renewable technologies, RES supporting schemes promote the RES industry and favor a reduction of the RES levelized cost of energy (LCOE) in the long run, making RES closer to the breakeven point. Lund (2011) adopts technology diffusion and endogenous learning models to analyze the role of energy and climate policies in boosting clean energy technologies towards cost grid parity. Using historical data on photovoltaic module prices, cumulative production, input prices for silicon and silver, De La Tour et al. (2013) identify an experience curve model and estimate that, thanks to innovation and learning-by-doing processes, the price of PV module will decrease by 67% from 2011 to 2020, bringing PV to the grid parity in the sunniest countries, such as Italy or California.

While these papers analyze the grid parity topic by focusing on the RES cost side, another strand of literature analyzes how RES supporting schemes and RES development is likely to impact on their revenues. Borenstein (2008) highlights that the RES market value strongly depends on the time at which electricity is produced. Since PV power generation is highly concentrated in the hours when price is higher than average due to peak demand, such a timing is likely to increase the PV market value.

Kettner (2012) finds that higher wind generation in the German market not only reduces the electricity price, but also increases its volatility[3]. She points out that the reduction of the electricity price combined with an increase of its variance is likely to reduce the economic

[3] See for example Jonsson et al. (2010) on the Danish market and Woo et al. (2011) on the Texan market.

returns from selling electricity and to lower the long run propensity to invest in new power capacity.

A relevant literature for the purpose of our paper focuses on the VF, an index which measures the value of electricity non-uniformly produced along the day with respect to a flat profile (Stephenson 1973). Fripp and Wiser (2008) calculate the wind VF dividing the wind-weighted average wholesale electricity price by the daily average market price and argue that this index compares the price that intermittent wind power actually receives with its hypothetical value in the case wind were invariant. Hirth (2013) reviews various studies that estimate the yearly VF of RES (among others Sensfuß and Ragwitz 2011; Green and Vasilakos 2012; Brown and Rowlands 2009). Moreover, by analyzing empirically a quite modest number of yearly observations, he finds that an increase of wind and solar penetration rates is associated with a reduction of their relative VFs. This suggests that RES penetration reduces the RES relative price more than on the daily average price, thus making RES grid parity more difficult to achieve than expected.

Sioshansi (2011) and Haas et al. (2013) analyze respectively the impact of wind and solar power in the energy markets and their analysis is helpful to understand why the VF for renewable sources is likely to decrease below 1. Sioshansi (2011) argues that, since wind technology cannot modulate production, it tends to have a lower market value with respect to other technologies that can store production and bid strategically. Similarly, Haas et al. (2013) show that an increase of PV capacity directly reduces the electricity price when solar power is available, while it indirectly increases the price at which electricity is offered by conventional power plants in the hours when RES are scarce. This suggests that RES penetration may reduce the RES market value more than the traditional sources' one. Apart from these important contributions, to the best of our knowledge, no paper has so far quantified the impact of RES penetration on the market value of traditional sources with respect to the market value of renewable sources themselves, and no paper has applied this type of analysis to the Italian case, which has experienced an exceptional PV increase.

3. Recent trends in the Italian energy market

As anticipated in the introduction, in a quite short period, Italian RES supporting schemes have boosted a tremendous growth of intermittent RES power capacity and generation. While a Green Certificates Scheme has been initially designed at the end of the '90s to support investments in renewable sources (wind power capacity in particular), since 2005 photovoltaic power capacity has been directly subsidized by a Feed-in Premium, named *Conto Energia*. The *Conto Energia* grants a subsidy for a period of twenty years for any KWh produced though PV technology.[4]

According to the International Energy Agency, the *Conto Energia* represents one of the most impressive PV supporting scheme in the world[5] (IEA 2011), and it has led to the highest

[4] Five different types of *Conto Energia* have been designed so far (I° *Conto Energia* entered into force in 2005, while the V° *Conto Energia* has been launched in 2012) and they vary, among various factors, with respect to: the type of plants which are entitled to receive the incentive (size, location, etc.); the authorization procedure; the amount of incentive granted per KWh produced (from 0.24 €/KWh to 0.44 €/KWh); the maximum amount of subsidies (cap) that can be granted. Since installation cost of a PV cell has decreased over time, also the subsidy per KWh produced has decreased from the first to the last Conto Energia.

[5] By the end of 2013 the five versions of the Conto Energia have overall supported the installations of 492,743 PV plants, corresponding to 16,317,565 KW of installed power capacity. The plants have produced 36,624,540,862 KWh

amount of solar installed capacity and production in the world (EPIA 2012, IEA 2013). Recently, the IEA declared that "From a market evolution perspective, Italy holds the world record when looking at the number of systems connected to the grid" (IEA 2013).

The Italian RES supporting schemes have promoted a tremendous growth of wind and PV installed capacity, from 1.6 GW in 2005 to 24.5 GW in 2012[6]: an "undisputed world record" according to the IEA. Thanks to these massive investments in RES power capacity, the RES share in the day-ahead wholesale power market has more than doubled in a relative short period: from 17% in 2005 to 31% in 2012 and 40% in 2013[7]. In detail, over the same period the PV share has increased from 0.5% to 12%. This sharp increase has been caused both by a contraction of electricity consumption and by a dramatic growth of RES power generation. After touching a peak in 2008, energy consumption decreased by 43 TWh in conjunction with the financial crisis and subsequent economic recession (in the phase 2008-2013), while wind and solar generation increased tremendously by 30 TWh over the same period (fig. 1).

[INSERT FIG. 1 HERE]

Both the increase in RES power generation and the reduction of demand have squeezed the residual demand that is covered by thermal sources, causing a contraction of gas power generation. This switch between RES and traditional sources should have favored a reduction of the daily average price, coherently with the theory of the *merit order effect*.

Indeed, fig. 2 shows a quite intuitive evidence of the *merit order effect*. In less than 10 years the solar share in the Italian energy mix increases by 12 percentage points against a 15% reduction of the gas share. Moreover, the switch between solar and gas market share is associated with the bearish trend of the wholesale energy price.

[INSERT FIG. 2 HERE]

4. PV and gas economic returns and the Value Factor

The aim of this paper is to test the differential impact that the PV penetration in the Italian electricity market has on the economic returns of PV and gas sources. Thus, we first look at the PV and gas daily revenues. To catch the non-uniform distribution of price and power generation by source along the day, rather than estimating daily revenues as the product of daily average price and average daily output, we first look at the daily sum of hourly revenues:

$$R_d^s = \sum_{t=1}^{24} p_t \, q_t^s \qquad (1)$$

Where R_d^s are the daily revenues of each technology source; s = gas, solar; p_t is the hourly price and q_t^s the hourly output of each energy source. Then, for each source we calculate the daily unit revenues, p_d^s, as the ratio of R_d^s with respect to the daily output of each energy source. Such unit revenues are therefore the weighted average price received by each technology each day:

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and the overall subsidy granted to PV power generation amounts to12.830 billion euro (source: GSE – Gestore Servizi Energetici).

[6] Source: Terna, the Italian Transmission System Operator

[7] These shares are elaborated on *on day-ahead power market data provided by the Gestore Mercato Elettrico (GME). 2013 data refer to the period January-October*

$$p_d^s = \frac{R_d^s}{\sum_{t=1}^{24} q_t^s} \quad (2)$$

Finally, we relate both the PV and gas daily unit revenues to the average daily price. By dividing the source's daily unit revenues p_d^s by the (unweighted) average daily price $\bar{p}$, we obtain an index representing the market value of each technology, also called Value Factor, VF:

$$VF = \frac{p_d^s}{\bar{p}} = \frac{\sum_{t=1}^{24} p_t q_t^s \Big/ \sum_{t=1}^{24} q_t^s}{\sum_{t=1}^{24} p_t \Big/ 24} \quad (3)$$

This approach allows us to avoid the excess noise that shows up with hourly data, while at the same time taking into account the unequal distribution of price and power generation by source along the 24 hours. In fact, the VF equals 1 only when the generation-weighted daily price that each source gains in the wholesale market equals the daily average price, that is when either power generation or the electricity price are distributed uniformly along the day. VF is greater than 1 when the price a given technology earns from selling electricity is higher than the daily average price. This takes place when power generation from a specific source is concentrated in those hours when the wholesale market clears at a price higher than its day average.

Fig. 3 reports the gas and solar annual revenues and their respective VFs. We highlight some interesting points on the solar and gas economic returns. First, while solar annual revenues increase over time, gas revenues show a decreasing trend. These trends are coherent with the switch between solar and gas share previously described. Even more interesting, in spite of the opposite trends of the gas and solar annual revenues, the gas value factor is always higher than the solar value factor and they show and opposite trend. In particular, the solar value factor first increases in the period 2007-2011 from a value lower than 1 to a value higher than 1, and then decreases again below 1 to reach the lowest level in 2013. Conversely, the gas value factor decreases in the period 2007-2011 but continues to be higher than 1, and then it increases again in the last two years. This opposite trend suggest that gas always sells its energy at a higher price than the average daily price, while PV initially sells electricity in the hours when the wholesale market clears at a price higher than its daily average and in the period 2012-2013 sells its energy at a lower level than the average price.

[INSERT FIG. 3 HERE]

5. The Data and the empirical approach

In this section we develop an empirical model to assess whether, and to which extent, solar penetration has caused a reduction of the solar market value. In particular, we are interested in determining whether solar penetration has a differential impact on the average daily price and on the weighted price earned by solar and gas producers.

We use hourly data available from the Italian *Gestore dei Mercati Energetici* (GME) for the Italian day-ahead wholesale electricity market from January 1st, 2007 until October 31st, 2013. Data are available since 2005; however, since the PV market share in 2005 and 2006 was negligible, we dropped those years from the dataset. The GME provides detailed data on 6 Italian (macro-)regions: North, Centre-North, Centre-South, South, Sicily and Sardinia, as well as Italy as a whole, on electricity prices, electricity demand and supply divided according to the type of energy sources. The data include all available energy sources, i.e. coal, gas, conventional hydro, hydro run-of-the-river, hydro pumped-storage, geothermic, wind, solar and OTS[8]. As stated in the introduction, we focus here only on solar and gas.

Given the discussion in section 4, our definition of "market value" is thus the value factor, VF, which we calculate using equation (3). Therefore, the hourly data are transformed into daily.

[INSERT TABLE 1 AND 2 HERE]

Table 1 shows summary statistics for the key variables of our analysis and Table 2 their year averages. A look at the latter confirms the discussion in the previous section: during the sample period, average electricity prices have been declining (with a large drop between 2008 and 2009, likely due to the first "wave" of the economic recession), while the share of PV has increased tenfold and that of gas has fallen. Moreover, both the unit revenues for PV and gas have dropped, but, while the former have dropped more than the latter, we always observe from 2007 until 2013 that $p_d^{pv} < p_d^{gas}$. As a result, also the value factor of gas is higher that that of PV and the two exhibited opposite trends.

Moving to a more formal analysis, in order to understand the determinants of VF, we run the regression:

$$VF_t^s = \alpha + \beta_1 sh\_gas_t + \beta_2 sh\_pv_t + \boldsymbol{\gamma}'\boldsymbol{D}_t + \varepsilon_t \qquad (4)$$

Where sh_gas and sh_pv are the market share of gas and PV respectively. While we are mainly interested on the impact of PV penetration on PV and gas VFs, we also control for the gas share, since it may impact on the price as well.

$\boldsymbol{D}$ is a vector of dummy variables to capture year, month and weekday effects. In fact, on the one hand, solar energy production cannot be programmed and ultimately depends on natural factors such as the weather and the number of hours of daylight. On the other hand, energy demand is likely to be different across weekdays, and, in particular, lower in the weekend. Apart from year, month and weekday dummies, we also include additional dummies for days when we observe very large outliers in our baseline regression, which may bias the estimation[9].

A limit of equation (4) is that the market share of each source depends on both electricity consumption and power generation; therefore, in order to disentangle their differential impact on the VF, we re-formulate (4):

$$VF_t^s = \alpha + \beta_1 supp\_gas_t + \beta_2 supp\_pv_t + \beta_3 demand_t + \boldsymbol{\gamma}'\boldsymbol{D}_t + \varepsilon_t \qquad (5)$$

where $supp\_gas_t$ and $supp\_pv_t$ equal the daily power generation by gas and PV respectively. Finally, instead of looking at the VFs we run the regressions specified in equation (5) using as dependent variable the sources' unit revenues, which is the numerator of the VF.

[8] OTS stands for "other traditional sources": sources other than coal and gas, for example oil

[9] We consider "large" an outlier which is more than 3.3 times the residuals standard deviation, in absolute value.

$$p_t^s = \alpha + \beta_1 supp\_gas_t + \beta_2 supp\_pv_t + \beta_3 demand_t + \boldsymbol{\gamma}'\boldsymbol{D}_t + \varepsilon_t \qquad (6)$$

Note that, in equation (6), we are mainly interested in the effect of PV energy production ($supp\_pv$) on the unit revenues of each of the two sectors. Since PV production is, by its nature, exogenous (suppliers cannot change their supply to react to fluctuations in the electricity price), then there is no simultaneity problem in our equation between the dependent variable and $supp\_pv$.

Equations (4) - (6) are the core of our empirical analysis. However, given the tremendous growth of solar power generation and the drop of electricity consumption the related time series may exhibit a non-stationary behavior. If this is the case, Equations (4) - (6) might be misspecified. Thus, before proceeding with the empirical analysis, we tested all series in Table 1 for the presence of a unit root[10]. While VF was always found to be I(0), the same is not the case for sh_gas_t and sh_pv_t, which were found to be I(1. Nevertheless, even when (some of the) variables in the regression are nonstationary, regression is valid as long as the regressors are cointegrated, i.e. as long as their linear combination is stationary (Hsiao, 1997). We therefore performed a Dickey-Fuller test on the residuals of equations (4) and (5) and found them to be stationary, meaning that we have cointegration *à la* Engle and Granger (1987).[11] An interesting insight of this result is that we therefore have an equilibrium relationship between the market shares of photovoltaic and gas in equation (4). This result summarizes the *merit order effect*: on the one hand, the growth in the PV market share along the sample was accompanied by a comparable fall in the share of Gas. Fossil fuels, in general, have been crowding out of the electricity market due to the increase in RES penetration.[12] On the other hand, when PV output during the year falls (for example, due to weather conditions), gas producers kick back in the market and compensate for such fall in production.

Given these promising results, in the next section we report the results of the estimation of equations (4) - (6), using Newey-West standard errors to correct for residual heteroskedasticity and autocorrelation.

6. Results

As a first step, we estimated equation (4) for the whole sample from 2007 until 2013.

Results are reported in Table 3 and 4, where the dependent variable is the value factor of photovoltaic and gas, respectively for the whole sample (2007-2013) and year by year. The full-sample estimates show that the VF of PV falls as the share of PV increases. In particular, a 1% increase in $share\_pv$ is associated with a drop in VF^{pv} of 0.44%.

[INSERT TABLE 3 AND 4 HERE]

[10] To check for non-stationarity, we performed the Augmented Dickey-Fuller and the KPSS test. Since the former tests for the existence of a unit root, while the latter tests for stationarity, using both helps to solve the problem of the low power of unit root tests. The number of lags in each ADF was chosen using the AIC and Schwarz's BIC Information Criteria. Results of the two tests always pointed to the same direction. Detailed results of the KPSS and ADF tests are available from the authors upon request.

[11] Results of the cointegration tests are available on request.

[12] Indeed, over the sample period the gas technology has been the marginal technology closing the market almost 60% of times, which thus makes it the first one to be displaced by PV growth (GME 2012 see Table 79, p.229).

This result confirms Hirth (2013) who found that the VF of solar energy sources dropped as their market share increased; however, it is much smaller, since Hirth finds that on a yearly basis a 1p.p. increase in PV share reduces the VF by 1.2%. Moreover, we find that solar penetration reduces its own VF more than the Gas VF. Indeed, an increase in the share of PV is associated with a reduction of the Gas VF, but only by 0.11% for a 1p.p. increase.

However, by performing simple stability tests on the coefficients, we find that they are not stable throughout the sample. This is totally reasonable, given the deep changes in the Italian energy mix and the large increase in the market share of renewable energy sources, photovoltaic in particular. Indeed, this could also imply that the relationship (4) is not linear, and the marginal effect of $share\_pv$ on the VF depends on the level of the former. Therefore, to tackle the issue of coefficient stability, we perform regression (4) using data for each sample year separately[13].

Results are reported in Table 4 and they tell quite a different story. Panel a. shows the results for PV market value. For a low value of the PV market share, in 2007 and 2008, its increase is actually positively associated with its VF, with a very large coefficient in 2007 possibly due to the still negligible share of PV in the market (0.4% on average). However, as the market share of PV further increases, the sign turns negative in 2009 and especially in 2012 and 2013, when $share\_pv$ increases most. In the last two years of the sample, when the market share of photovoltaic increases to 9.3% and 11.8% respectively (see Table 2), a 1% increase in $share\_pv$ is associated with a fall in the VF of 1.9% and 2.8% respectively, much higher than our full sample estimate and that of Hirth (2013).

Can the same pattern be observed for Gas? Yes, but in the opposite direction: as shown in Table 4 panel b., while the increase in PV penetration reduces the gas VF in the first years of the sample, the sign of the coefficient is positive and significant in 2012 and 2013, when a 1% increase in the share of PV increases VF^{gas} by up to 0.5%.

The limitation of the results obtained from estimating (4) is that, since the market share of source s is calculated as supply of that source divided by total demand, one could argue that changes in the market share also come as a result of changes in total demand (for example, the drop in demand due to the recession in the sample period), and therefore our results may be driven by demand rather than supply effects.

[INSERT TABLE 5 HERE]

We therefore estimate equation (5) where the two effects are included separately. Again, we perform the regression year by year to tackle the issue of coefficient stability. Results are reported in Table 5, panels a. and b. First of all, electricity demand has a positive sign, as we would expect; the drop in demand in 2009 and 2012-13 due to the recession has therefore contributed to a drop in the market value of both energy sources, other things being equal, but more on PV than on Gas. However, the impact on the photovoltaic is stronger, possibly due to the fact that the contraction of demand has mainly taken place in the daytime, when solar

[13] Alternatively, to capture a nonlinear relationship between *share_pv* and *vf*, we could add as regressors the square of the market share of PV or even the cube. However, by performing the regression year-by-year we maintain a flexible approach while still having a sufficiently large number of observations. While performing the regression controlling for the square of *share_pv*, confirmed our results, the analysis performed on the whole sample still suffers from coefficient instability. Therefore, dividing the sample by year seems more appropriate.

generation – which cannot be programmed and therefore there cannot bid strategically – is mainly concentrated. An increase in the PV power generation was positively associated with its VF in 2007 and 2008, but this effect turned negative since 2009 and in particular in 2012 and 2013, thus confirming our previous result. While a contraction of electricity consumption has contributed to the reduction in the market value of PV, the increase of PV power generation has reduced its profitability as well. Moreover, higher supply of PV has a positive effect on the VF of gas, if any.

[INSERT TABLE 6 HERE]

When we focus on unit revenues (equation (6)), the picture becomes even clearer. Again, in the case of photovoltaic producers (Table 6, panel a.), a higher demand is associated with higher unit revenues. When we look at the effect of solar energy supply on its unit revenues, again we see that while supply had a positive effect on unit revenues in 2007 and 2008, then the coefficient changed sign. In 2012 and 2013, a 1% increase in the supply of solar energy reduced its production-weighted relative price by 0.18-0.35%, a pretty large amount. While one could say that the negative sign might be due to producers supplying less when the prices is low, i.e. that there could be a problem of reverse causality here, note that, as we discussed in the previous section, in this case the design of the market and the characteristics of the supply make reverse causality not possible: on the one hand, photovoltaic production depends on weather conditions, thus it cannot be programmed and it cannot bid strategically like other technologies, i.e. cut supply when price is low and increase it when the price goes up; on the other hand, it is dispatched with legal priority. Therefore, the quantity supplied by PV can be considered as entirely exogenous.

In the case of gas unit revenues (panel b. in Table 6), higher supply of gas and higher electricity demand are associated with higher unit revenues, confirming our previous results.

7. Interpretation of the results

Our results suggest that, the period 2007-2013, the increase of the PV share is on average associated with a reduction of its market value, measured by its VF and unit revenues. Interestingly, we have found that the relation between the PV share and its VF (and unit revenues) is not constant over time, while it seems to depend on the degree of PV penetration. For very low levels of PV generation, an increase of the PV share (and generation) positively impacts on its market value, while, as the PV share increases, this impact marginally decreases to become even negative in 2012 and 2013, when the PV share exceeds 10%. An opposite trend occurs when looking at the Gas VF: an increase of the PV share is first associated with a reduction of the Gas VF, while this relation becomes positive for a further PV penetration.

The main intuition behind these results can be gained by looking at the evolution of the hourly distribution of PV and Gas power generation and at the trend of the peak and off-peak prices. First, the growth of solar power generation has been highly concentrated during the daytime around noon (fig.4 panel a.). Second, the level of gas production has decreased over the years and, most importantly, its peak in production has switched from the morning to the nighttime. In other terms, the merit-order effect (daytime switch between solar and gas) has pushed gas producers to supply most of their electricity during off-peak hours (fig. 4 panel b.).

[INSERT FIG. 4 PANEL a. - b. HERE]

Moreover, PV penetration is associated with a reduction of the spread between the peak and off-peak price[14]. In particular, the electricity price has decreased in the peak hours – when PV generation is highly concentrated – while it has increased in the off-peak time, when PV is almost absent from the market and production from traditional sources grows.

[INSERT FIG. 5 HERE]

Given these data, we interpret our main findings in the following way. The initial PV penetration is positively correlated with its VF because it has taken place mainly in those hours when the electricity price peaks above its average daily value. The relative price that PV producers have initially earned in the peak-hours has been higher than the daily average price (VF>1). At the very beginning the PV penetration is also negatively associated with the Gas VF because gas producers have been driven out from the market in the peak time, thus lowering the relative price they perceive compared to the base price (VF<1).
Subsequently, two main effects interact and contribute to explain why the solar VF decreases and gas VF increases as PV share increases. First, as PV generation further increases, displacing traditional sources in the daylight (peak) hours, it reduces the peak price, thus pushing down the relative price that PV producers earn in those hours and marginally lowering their unit revenues (numerator of the solar VF). The reduction of the peak price lowers also the average daily price (denominator of the solar and gas VF), but not the relative price earned by gas producers, as in those hours they are driven out from the market. As a result, the solar VF decreases (numerator decreases relatively more the denominator), while the gas VF relatively increases (denominator decreases more than its numerator).
Moreover, in the off-peak hours solar is almost absent from the market and traditional sources can exert their temporary higher market power, thus increasing the off-peak price to compensate for daylight hours losses. In other terms, in the off-peak time traditional sources bid strategically and increase their market value with respect to renewable sources: the increase of the off-peak price increases both the unit revenues perceived by gas producers and the daily average price, but not the price earned by solar producers. As a result, the solar VF tends to further decrease (denominator increases while the numerator does not), while the gas VF increases (numerator increases more than the denominator). Our results and this interpretation are consistent with Sioshansi (2011) and Haas et al. (2013).

8. Conclusions and policy implications

Several papers have found that RES penetration lowers the wholesale electricity price. This merit-order effect does not only impact on consumers' welfare, but it affects the economic returns of RES and traditional sources as well. Since both the electricity price and power generation from renewables and traditional sources are not uniformly distributed across the 24 daily hours, the price that RES and traditional sources gain from the sale of electricity differs

[14] With the term peak price we refer to the average price registered during the daily hours (08.00-19.00), while the term off-peak price refers to the average price registered during the nightly hours (19.00-08.00).

from the average daily price. Therefore, RES penetration may affect the economic returns of RES and traditional sources unevenly. Given this premise, this paper has tested the differential impact of RES penetration on the market value of RES and traditional sources in the Italian power market. We have focused on PV and gas sources, as the former has experienced the most significant growth, while the latter covers the highest share of the national energy mix. The market value of the various energy sources has been measured by both the unit revenues that they earn when selling electricity and by their VF, a ratio between the sources' unit revenues and the average daily price.

We have found that solar penetration has a differential impact on the average daily price – usually used to assess the impact of RES penetration on consumers' welfare – and on the weighted price earned by solar and gas producers. Not only the increase in solar generation reduced the electricity price, as widely argued. This reduction has taken place mainly in the hours when solar generation is highly concentrated, thus lowering the solar marginal revenues more than the gas ones. In particular, we have found that the relation between the PV share and its market value is not constant over the years, while it depends on the degree of PV penetration. An increase in the PV share raises its VF when the former is low, but the relationship becomes negative as the PV market share increases. Conversely, an increase of the PV share is first associated with a reduction of the Gas market value, while this relation becomes positive for a higher PV penetration. Coherently with our results, the opposite trend of peak and off-peak prices suggests that PV penetration directly reduces the electricity peak price in the hours when solar is highly concentrated in the market, thus lowering the relative price earned by solar producers. This implies a marginal departure from the grid parity condition. Conversely, traditional sources bid strategically and increase the electricity off-peak price when PV is absent from the market, thus increasing the relative price earned by gas producers. As a result, as solar penetration increases the price that solar producers gain is lower than the daily average price, implying a marginal reduction of the solar VF. Conversely, the price that traditional sources receive in the off-peak time is higher than the daily price, implying an opposite marginal increase of the gas VF associated by the PV penetration.

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Table 1. Summary statistics, 2007-2013

Variable	Obs	Mean	Std. Dev.
p_t	2496	71.07	13.94
p_d^{sol}	2496	71.22	15.02
p_d^{gas}	2496	74.26	14.64
sh_sol_t	2496	0.0434	0.0434
sh_gas_t	2496	0.4890	0.0813
VF^{solar}	2496	1.000	0.0631
VF^{gas}	2496	1.045	0.0259

Table 2. Year averages

	2007	2008	2009	2010	2011	2012	2013*
p_t	70.99	86.99	63.72	64.12	72.23	75.48	62.47
p_d^{pv}	69.70	87.67	64.92	65.99	74.46	74.24	59.58
p_d^{gas}	74.58	90.58	67.43	66.53	74.58	78.81	65.87
sh_pv_t	0.004	0.018	0.023	0.025	0.035	0.093	0.118
sh_gas_t	0.520	0.508	0.480	0.551	0.526	0.447	0.371
VF^{pv}	0.982	1.008	1.019	1.028	1.030	0.980	0.945
VF^{gas}	1.048	1.040	1.058	1.037	1.032	1.045	1.058

*Data for 2013 finish in October 31st.

Table 3. Value factor and market shares, 2007-2013

	VF^{pv}	VF^{gas}
sh_gas_t	0.070*** (0.025)	-0.134*** (0.014)
sh_pv_t	-0.441*** (0.047)	-0.113*** (0.024)
$Const$	0.992*** (0.015)	1.143*** (0.008)
YMD	YES	YES
R^2	0.622	0.478

Note: YMD= year, month and weekday dummies. The first line indicates the dependent variable. N = 2495. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

Table 4. Yearly Value Factor regressions

a. Photovoltaic

	2007	2008	2009	2010	2011	2012	2013
sh_gas_t	0.204***	-0.001	-0.006	-0.012	0.152**	-0.146*	-0.667**
	(0.042)	(0.008)	(0.027)	(0.028)	(0.061)	(0.126)	(0.150)
sh_pv_t	33.77***	0.266***	-0.622**	0.084	0.001	-1.927***	-2.843***
	(2.241)	(0.052)	(0.256)	(0.204)	(0.235)	(0.217)	(0.270)
$Cons$	0.757***	0.997***	1.024***	1.027***	0.953***	1.208***	1.545***
	(0.023)	(0.004)	(0.021)	(0.016)	(0.035)	(0.066)	(0.081)
MD	YES	YES	YES	YES	YES	YES	YES
R^2	0.933	0.566	0.688	0.628	0.587	0.737	0.768
N	365	366	365	365	365	366	304

Note: Dependent Variable is VF^{pv}. MD= month and weekday dummies. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

b. Gas

	2007	2008	2009	2010	2011	2012	2013
sh_gas_t	0.053**	0.028*	0.026	-0.098***	-0.014	-0.044*	-0.020
	(0.031)	(0.027)	(0.033)	(0.021)	(0.024)	(0.030)	(0.061)
sh_pv_t	-2.474**	0.063	-0.530**	-0.093	-0.107	0.184**	0.488***
	(1.181)	(0.124)	(0.238)	(0.133)	(0.114)	(0.067)	(0.106)
$Const$	1.065***	1.068***	1.075***	1.113***	1.082***	1.088***	1.020***
	(0.018)	(0.014)	(0.023)	(0.013)	(0.016)	(0.016)	(0.034)
MD	YES	YES	YES	YES	YES	YES	YES
R^2	0.861	0.791	0.747	0.672	0.721	0.653	0.673
N	365	366	365	365	365	366	304

Note: Dependent Variable is VF^{gas}. MD= month and weekday dummies. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

Table 5. Modified Yearly Value Factor regressions

a. Photovoltaic

	2007	2008	2009	2010	2011	2012	2013
$supp\_gas_t$	0.003	-0.006*	-0.013	-0.013*	0.009	-0.063*	-0.118**
	(0.026)	(0.005)	(0.007)	(0.012)	(0.024)	(0.040)	(0.048)
$supp\_pv_t$	0.279***	0.003***	-0.018***	-0.013*	0.005	-0.136***	-0.268***
	(0.021)	(0.001)	(0.004)	(0.007)	(0.010)	(0.016)	(0.034)
$demand_t$	-0.049*	0.008	0.066***	0.045**	0.097**	0.274***	0.355***
	(0.047)	(0.010)	(0.018)	(0.021)	(0.039)	(0.047)	(0.098)
$Const$	-0.610*	0.945***	0.455**	0.467**	-0.471*	-0.460*	0.592
	(0.375)	(0.098)	(0.193)	(0.212)	(0.408)	(0.389)	(1.286)
MD	YES	YES	YES	YES	YES	YES	YES
R^2	0.943	0.564	0.724	0.640	0.598	0.728	0.739
N	365	366	365	365	365	366	304

Note: Dependent Variable is VF^{pv}. MD= month and weekday dummies. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

a. Gas

	2007	2008	2009	2010	2011	2012	2013
$supp\_gas_t$	0.003	-0.007	-0.019*	-0.045***	-0.030***	-0.018*	-0.028*
	(0.014)	(0.012)	(0.012)	(0.009)	(0.008)	(0.011)	(0.019)
$supp\_pv_t$	-0.002	0.002*	-0.005*	0.002	-0.007**	0.004	0.034***
	(0.003)	(0.001)	(0.004)	(0.003)	(0.003)	(0.006)	(0.011)
$demand_t$	0.035**	0.048*	0.121***	0.062***	0.064***	0.008	-0.026
	(0.028)	(0.026)	(0.028)	(0.019)	(0.016)	(0.018)	(0.036)
$Const$	0.582**	0.481*	-0.285	0.776***	0.657***	0.657***	1.157***
	(0.266)	(0.252)	(0.300)	(0.195)	(0.196)	(0.196)	(0.174)
MD	YES	YES	YES	YES	YES	YES	YES
R^2	0.860	0.797	0.765	0.675	0.738	0.638	0.652
N	364	366	365	365	365	366	304

Note: Dependent Variable is VF^{gas}. MD= month and weekday dummies. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

Table 6. Unit Revenues regressions

a. Photovoltaic

	2007	2008	2009	2010	2011	2012	2013
$supp\_gas_t$	-0.120*	0.168*	0.041	0.374***	0.357***	0.446***	0.278**
	(0.116)	(0.124)	(0.152)	(0.100)	(0.074)	(0.089)	(0.129)
$supp\_pv_t$	0.569***	0.002	-0.092***	-0.008	-0.036	-0.175***	-0.346***
	(0.089)	(0.016)	(0.032)	(0.022)	(0.036)	(0.048)	(0.075)
$demand_t$	1.399***	0.418*	0.980**	0.265*	-0.048	0.235*	0.117
	(0.191)	(0.259)	(0.399)	(0.199)	(0.121)	(0.172)	(0.250)
$Const$	-17.82***	-3.433*	-8.962**	-4.230**	0.857	-2.698*	-2.949
	(1.669)	(2.336)	(3.987)	(1.912)	(1.365)	(1.492)	(3.516)
MD	YES	YES	YES	YES	YES	YES	YES
R^2	0.864	0.612	0.608	0.428	0.649	0.726	0.651
N	365	366	365	365	365	366	304

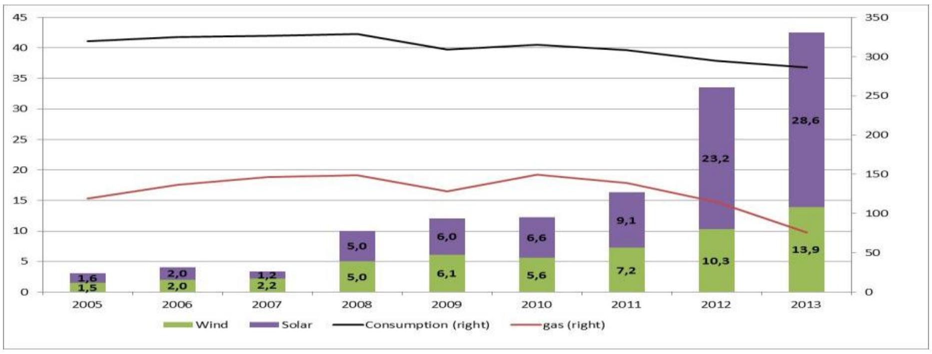
Note: Dependent Variable is p^{pv}. MD= month and weekday dummies. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

b. Gas

	2007	2008	2009	2010	2011	2012	2013
$supp\_gas_t$	-0.121*	0.161*	0.030	0.344***	0.316***	0.516***	0.447***
	(0.109)	(0.125)	(0.153)	(0.100)	(0.064)	(0.072)	(0.070)
$supp\_pv_t$	0.034	0.000	-0.077**	-0.017	-0.047*	-0.015	0.014
	(0.033)	(0.015)	(0.033)	(0.022)	(0.030)	(0.048)	(0.034)
$demand_t$	1.550***	0.476*	1.033***	0.277*	-0.098	-0.096	-0.316**
	(0.178)	(0.262)	(0.397)	(0.203)	(0.110)	(0.146)	(0.152)
$Const$	-15.52***	-4.056*	-9.630**	-3.866**	2.223*	-0.723	2.809*
	(1.632)	(2.362)	(3.966)	(1.932)	(1.243)	(1.325)	(2.181)
MD	YES	YES	YES	YES	YES	YES	YES
R^2	0.884	0.642	0.609	0.400	0.673	0.643	0.565
N	364	366	365	365	365	366	304

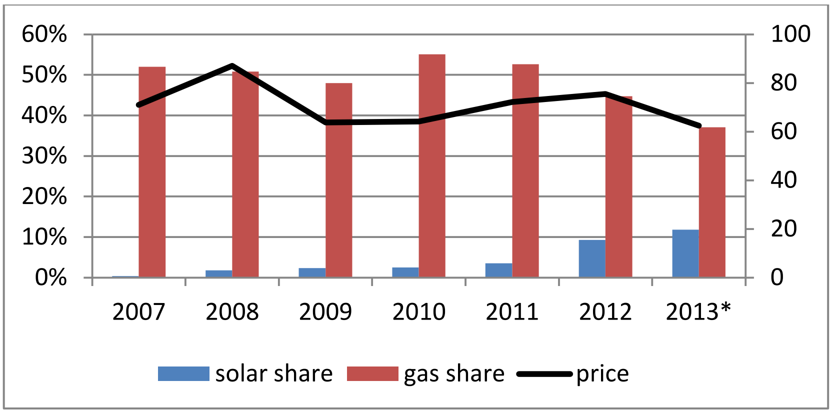
Note: Dependent Variable is p^{gas}. MD= month and weekday dummies. Robust standard errors in parenthesis. *** denotes significance at 1%; ** denotes significance at 5%, * denotes significance at 10%.

Fig. 1- Energy demand, Gas, Wind and solar generation in the day-ahead Italian market* (TWh)



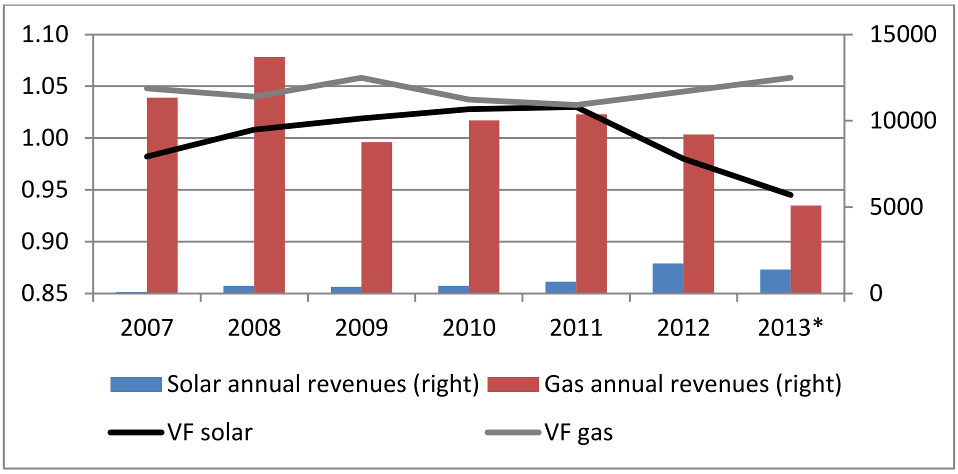
*Source: own elaboration on day-ahead power market data - Gestore Mercato Elettrico (GME) *2013 data refer to the period January-October*

Fig. 2 – Gas and Solar share (%) and price trend (€/MWh)



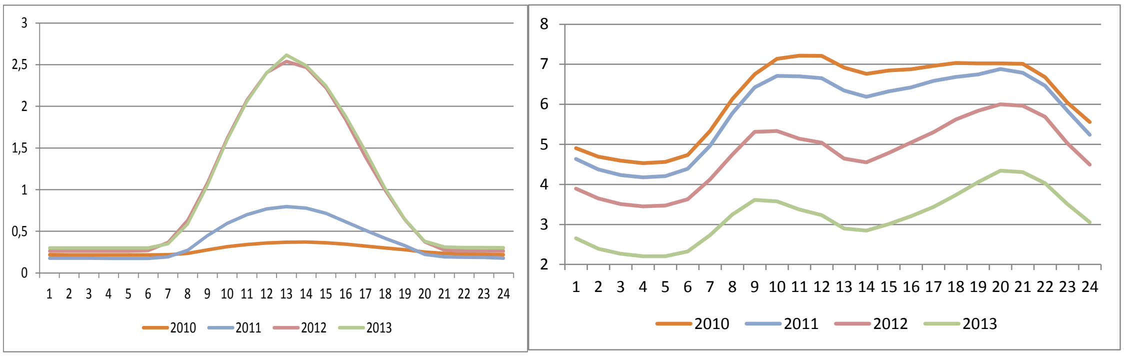
*Source: own elaboration on day-ahead power market data - Gestore Mercato Elettrico (GME) *2013 data refer to the period January-October*

Fig. 3 – PV and Gas Factors (left) and annual revenues (million euros) (right)



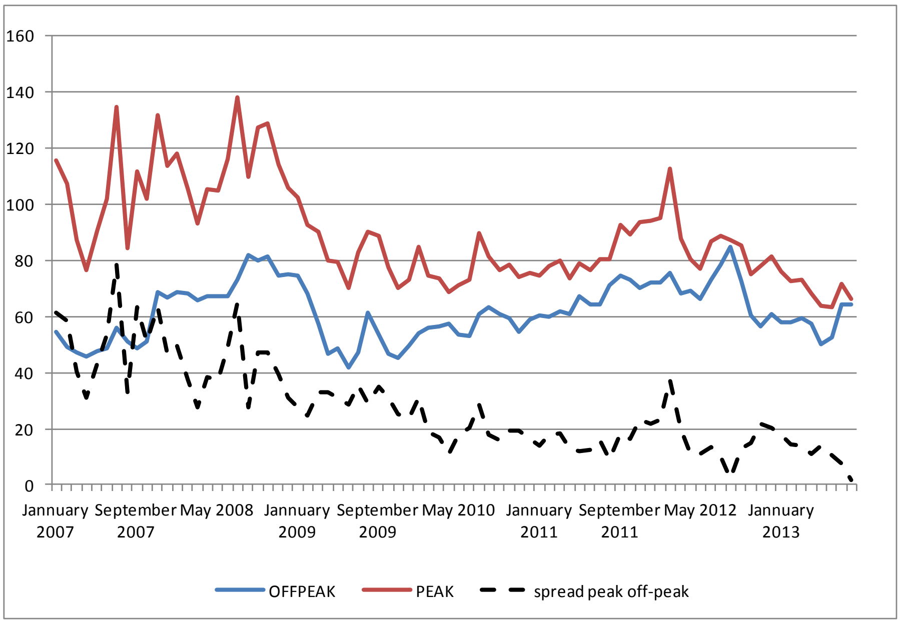
*Source: own elaboration on day-ahead power market data - Gestore Mercato Elettrico (GME) *2013 data refer to the period January-October*

Fig. 4 - Hourly distribution of solar (left) and gas (right) power generation over the period 2010-2013 (TWh)



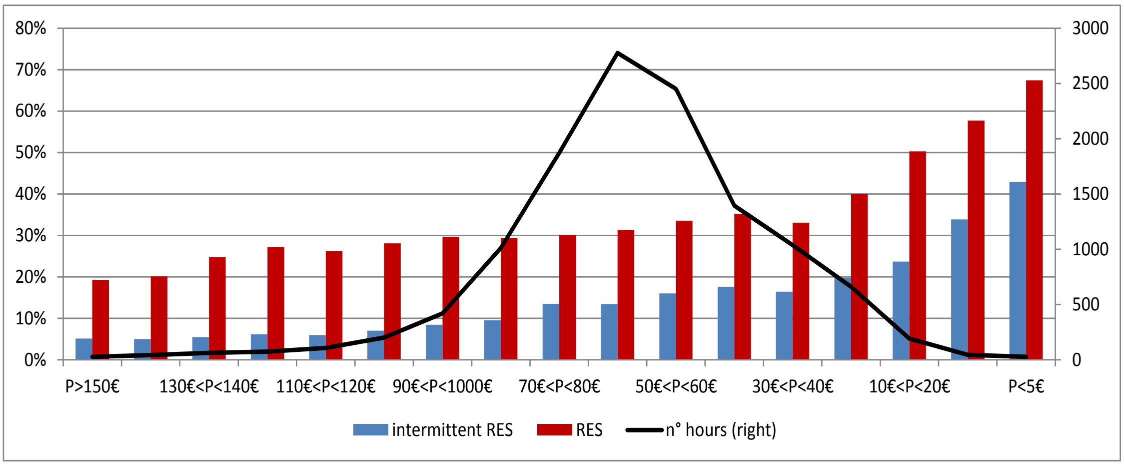
Source: own elaboration on Gestore Mercato Elettrico (GME)

Fig. 5 – peak and off-peak price during the period 2005-2013



Source: own elaboration on Gestore Mercato Elettrico (GME)

Fig. 6 – distribution of RES share and number of hours across price size classes in 2012-2013*



*Source: own elaboration on Gestore Mercato Elettrico (GME) *2013 data refer to the period January-October*